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Abstract

Understanding and harnessing interactions between light and matter have been an enduring endeavor in human history and a centerpiece of modern science and technology developments, and given birth to numerous brilliant inventions such as light emitting diodes and lasers that completely changed the world. Quantum Cascade (QC) lasers as one of the newest achievements in this rank have motivated a broad range of exciting potential applications such as high-sensitivity trace gas sensing, non-invasive glucose monitoring, free-space optical communication, etc. Although the QC laser technology has been undergoing a rapid and steady development phase ever since its invention in 1994, further improvements in aspects such as output power, efficiency, spectral purity and cost-effectiveness are indispensable for large-scale implementations of QC laser based application systems. To meet such ends, we explore in this thesis novel approaches from the device structural design perspective to further improve the overall performance of QC lasers and lower their fabrication cost, while at the same time assess new application possibilities.

Exploiting the extraordinary design flexibility of the QC laser band-structure, we demonstrate a major step forward in the power performance of QC lasers by employing a novel ultra-strong coupling design strategy. A record QC laser wall-plug efficiency of ~50% is achieved. Such high-performance QC lasers enable our proof-of-concept implementation of a mid-IR backscattering light detection and ranging (LIDAR) system. Moreover, the ultra-strong coupling design strategy is also applied to realizing QC lasers with broad-band optical gain. QC lasers with optical gain spectrum width corresponding to ~40% of the radiative transition energy are demonstrated.
As single-mode operation of QC lasers is indispensable for most sensing applications, we further explore unconventional laser cavity designs to achieve single-mode QC lasers more cost-effectively. Two fundamentally different approaches, i.e., the monolithic coupled-cavities and the asymmetric Mach-Zehnder interferometer type cavities, are proposed and experimentally verified. Both types of cavities are capable of establishing strong wavelength selectivity and facilitating single-mode operation of QC lasers without the need of sub-wavelength periodic feedback structures, and therefore are much more cost-effective than conventional single-mode QC laser technologies.

Our explorations presented in this thesis widen the territory for the QC laser research field and shed light on new directions for future explorations.
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The ancient Chinese philosopher Confucius said that whenever you walk with two other people side by side, at least one of them can teach you something. Through my personal experiences, I always found this very well said. During my five-year study and research at Princeton University, I was very fortunate to have been able to work with a lot of people, learning so many things as well as receiving so much help and support from them. I would like to take this great opportunity, which one does not get very often, to express my sincere gratitude to all of them.

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Chapter 1

Introduction

Electrons and photons are the two earliest discovered elementary particles in modern physics. This is perhaps not a surprise at all, since they are so abundant in nature and we directly interact with them or their macroscopic representations, electricity and light, all the time. Even in ancient times, it was known that amber rods could attract certain light materials after rubbing against a piece of fur, a phenomenon of static electricity. It is not necessary to say much on this issue about light, from which the plants get energy and by which we see things. Understanding and harnessing electricity and light, electrons and photons, has always been one of the core pieces of the study of physical sciences and the development of technologies. On the other hand, electrons and photons are rarely two different subjects of study, they frequently appear intertwined in various settings, from the observation of lightening to the discovery of photoelectric effect, from the invention of light bulbs to the demonstration solar cells. At the dawn of modern physics we learned that the strong interactions between electrons and photons are indeed governed under the elegant law described by the Maxwell’s equations.

The development of modern physics allowed us to study electrons, photons and their interactions on a more fundamental level, which yielded a series of important discoveries and great inventions. The rise of the field of optoelectronics extended the tradition of tailoring the interactions between electrons and photons to create game-changing applications. The most (literally) brilliant example in the recent half-century is the invention and the subsequent rapid development of lasers. This field is already fruitful but still young and full of energy. New lasers are constantly added to the laser family, stirring excitement across the horizon. One of the youngest with a distinct look of sophistication is the Quantum Cascade (QC) laser, the focus of this work.
1.1 A brief history of the invention of QC lasers

The birth of QC lasers was by no means an accident, or an unexpected glittering gemstone discovered along the way to some other destiny. It was, on the contrary, another spectacular triumph for modern physical sciences and technology development long sought after by generations of scientists and engineers. Even more splendid, it proves to be a worthwhile pursuit, for QC lasers now have far-reaching technological impact on various fronts of the human society, and their development is still growing rapidly. Whenever something like this happens, it is always pleasant to pause for a moment and recollect its fascinating and inspiring success stories.

Indeed, it was a long way to come. The first successful demonstration of QC lasers by Faist et al. in 1994 [1] at the Bell Labs was built upon several layers of foundations. Tracing it back, one would find a good starting point to be the invention of laser (which of course has its own fascinating stories worth appreciating, but here let us not go any further). The idea of a laser operating in the visible and infrared wavelength range was first developed in depth by Charles Townes and Arthur Schawlow in the late 1950s [2] (also at Bell Labs) following the successful development of masers earlier; and the first operating laser, which was a solid-state laser based on a ruby crystal, was demonstrated by Theodore Maiman in 1960 [3]. Ever since this groundbreaking work, the development on various kinds of lasers experienced rapid progresses, with the first gas laser demonstrated later in 1960 [4] and the first semiconductor laser based on GaAs reported in 1962 [5]. The use of semiconductor materials for lasers has its unique advantages such as the possibility to pump electrically and to realize extremely compact devices, therefore it immediately became a vigorous research field and soon reached another milestone: a room-temperature AlAs-GaAs double-heterostructure laser demonstrated by Alferov et al. [6]. The introduction of III-V heterostructures to semiconductor lasers had far-reaching impact on the development of various kinds of semiconductor lasers in the years that followed [7-9], including QC lasers which conceptually originate from a more complex type of semiconductor heterostructures: the semiconductor superlattice.
The concept of semiconductor superlattice, which consists of periodically alternating thin layers (thickness is on the order of nm) of two different semiconductor materials (well material and barrier material), was first proposed and studied by Esaki and Tsu in a seminal paper [10]. The resonant tunneling characteristic of the electron transport in superlattice structures immediately stimulated interest of their applications in different fields, such as in high-speed electronics. Almost at the same time, the potential application of the semiconductor superlattice in optoelectronics was introduced by Kazarinov and Suris [11, 12]. In their renowned papers, it was proposed that when the superlattice band-structure is tilted by an external electric field, tunneling of electrons (or holes) from the ground state of one well to the excited state in the next well can be assisted by the emission of a photon with energy equal to the energy difference between the two states, and therefore provides optical gain (the carrier population on the upper laser level which is the ground state of the first well is naturally higher than that on the lower laser level which is the excited state of the second well). This is the conceptual foundation for QC lasers, a type of laser based on intersubband optical transitions in highly confined semiconductor heterostructures such as quantum wells (QW). For typical III-V heterostructure material systems, such optical transitions are expected to be in the mid-infrared to far-infrared wavelength range which is of tremendous interest for applications such as spectroscopy or free space communication. Unlike band-to-band transitions with the transition energy relatively fixed by the materials concerned, intersubband transitions provide the highly desired flexibility of controlling the transition energy by simply tailoring the thicknesses of the superlattice material layers. Another obvious and thrilling advantage for such a device operation concept is that the transitions are repeated in each period of the superlattice through sequential tunneling and relaxation (from the excited state down to the ground state) of the carriers, and thus the optical gain is multiplied. Such attractive prospects triggered the onset of the more than two decades quest for an operating laser based on such a concept, the first QC laser.

A frequent scenario in the history of science and technology development is that an elegant and beautiful idea takes a long time to be tested or demonstrated due to practical limitations on
experimental capabilities. This is also what happened to the demonstration of QC lasers. It is not difficult to imagine that constructing a semiconductor superlattice structure composed of hundreds of thin layers of different materials with high (single atomic layer) accuracy in the layer thicknesses and abrupt interfaces is not a trivial job. In addition, the two (or more) different materials and the substrate the structure is based upon may have different lattice constants, therefore managing the strain in the structure is also a critical task since a high strain can alter the material properties and degrade the device performance [13]. Fortunately, the development of molecular beam epitaxy (MBE) [14-16] and metalorganic chemical vapor deposition (MOCVD) [17] technologies started at around the same time eventually lead to the capability of achieving high-quality semiconductor heterostructures in a few material systems, and paved the way for the extensive investigations of intersubband transitions in QW and superlattice structures [18] and the development of band-structure engineering [19], which necessarily preceded the advent of QC lasers. The systematic study of intersubband absorption in various material systems allowed for extraction of the basic material parameters required for accurate band-structure engineering which later proved to be crucial for designing QC lasers. With gradual progress, intersubband emissions were observed in both QWs and superlattices [20-23] several years prior to the demonstration of the QC laser.

In the early 1990s, the tools and knowledge necessary for making a superlattice based intersubband laser were readily available [24-27], the last piece of the puzzle was a good band-structure design. The original proposal by Kazarinov and Suris requires the operation of the superlattice at a bias where the ground state in the first well is higher in energy than the first excited state of the second well but below the second excited states. However, it was found in later studies of superlattice structures that such a bias configuration is unstable and that the superlattice would divide into different electric field domains [28]. Therefore, different device operation schemes were proposed to avoid operating in this unstable regime [29-32]. Finally, with a carefully engineered band-structure which essentially formed a four-level laser system (levels 1−4), population inversion between level 3 and level 2 was achieved thanks to their dramatically different longitudinal optical
(LO) phonon scattering lifetime; the first QC laser based on InGaAs/AlInAs on InP operating at \( \sim 4.2 \, \mu \text{m} \) was born [1].

Immediately, the QC laser field attracted tremendous attention from different communities and witnessed rapid progress: QC lasers at different wavelengths quickly mushroomed [33-35] with the first THz QC laser reported in 2002 [36]; continuous-wave (CW) [37] and room-temperature [38] operations were demonstrated one after another; different laser cavity structures were successfully employed to improve the spectral characteristics [39, 40]; QC laser based spectroscopy and sensing applications also followed closely [41], etc. Even today, all these constitute a still very active research field with constantly emerging exciting advances. The underlying driving force for such long-lasting enthusiasm in QC lasers is their unique inherent technological advantages, design flexibility, and their potentials for wide ranging applications.

1.2 Fundamentals of QC lasers

Like most other types of lasers, QC lasers also consist of two key components, the gain medium and the laser cavity. In addition, due to the need to transport charge carriers from one period of active region, i.e., where the radiative intersubband transitions take place, to the next, injectors are employed as a key component of the laser active core to fulfill such a task. This section is dedicated to a brief review of the basic structure and the underlying principles of each of these key components of QC lasers, followed by an introduction to the typical fabrication of QC lasers.

1.2.1 Gain medium of QC lasers

Ever since the first functioning QC laser design, the optical gain of QC lasers has mainly been based on intersubband transitions in multiple-QW structures (the active region), though structure details changed from design to design. Since all QC lasers so far have been based on intersubband transitions in the conduction band of the heterostructures, the discussion here also assumes that only
the conduction band is involved and that the charge carriers are electrons. In order to understand such intersubband transitions, one may start from a single QW. In a single QW shown in Fig. 1.1(a), electrons can undergo intersubband transitions, such as absorption, spontaneous emission, and stimulated emission between the quantized energy levels (states) in the QW, and the electromagnetic field involved must have an electric field component perpendicular to the material layers. With Fermi’s golden rule, one can derive the rate for the intersubband transitions and finds that they are proportional to the square of the dipole matrix element:

$$W_{i,f} \propto |\langle i | z | f \rangle|^2$$  \hspace{1cm} (1.1)

where $i$ is the wavefunction for the initial state and $f$ is the wavefunction for the final state, $z$ is the direction perpendicular to the material layers [26, 42]. For a symmetric single QW, $\langle i | z | f \rangle \neq 0$ only when $i$ and $f$ have different parities, therefore the transitions $E_2$ to $E_1$ and $E_1$ to $E_0$ in Fig. 1.1(a) are allowed, but the transition $E_2$ to $E_0$ is forbidden. Such a selection rule for intersubband transitions in a single QW is a result of the QW’s and hence the wavefunctions’ symmetry.

However, for a single QW subject to an external electric field or a multiple-QW structure like the one in Fig. 1.1(b), the structural symmetry is broken and the intersubband transition rates are still described by Eqn. (1.1), therefore transitions between any two levels are possible. When employing such a multiple-QW structure as the active region of a QC laser, one optimization strategy is to maximize the dipole matrix element and therefore the strength of the radiative transition without compromising other design considerations. This strategy leads to a high degree of spatial overlap between the upper laser state and the lower laser state, making the transition “vertical” [37, 43].
Fig. 1.1 (a) Schematic for intersubband transitions in a symmetric QW without bias field. (b) Schematic for a multiple-QW structure.

On the other hand, besides high transition strength, population inversion between the upper and the lower laser states also needs to be achieved to produce optical gain. In a multiple-QW structure, the spontaneous emission lifetime is on the order of 1 ns while the non-radiative carrier relaxation time is on the order of 1 ps due to the fast LO-phonon emission process [24]. At first glance, this seems to be an awful system to achieve population inversion and therefore lasing because of the fast carrier relaxation. However, for achieving population inversion, what matters is the ratio of the upper laser state lifetime to the lower laser state lifetime, not the absolute values. Since the intersubband relaxation time due to LO-phonon emission is highly energy dependent, with the minimum at the LO-phonon energy (~34 meV in InGaAs/AlInAs) and significantly longer at larger transition energies, it is possible to obtain a much shorter lower laser state lifetime (on the order of 0.1 ps) by placing another subband energy level about one LO-phonon energy below the lower laser state, thanks to the design flexibility offered by band-structure engineering. Such LO-phonon depopulation scheme is applied widely in QC laser designs. In addition to reducing the lower laser
state lifetime, population inversion can also be improved by increasing the upper laser state lifetime. One way to achieve a longer LO-phonon emission dominated relaxation time for the upper laser state is to reduce its spatial overlap with the lower laser state, making the transition “diagonal” [44] instead of “vertical”. However, a diagonal design also reduces the transition strength. In this sense, the vertical design and the diagonal design have complementary advantages and disadvantages. Whether to employ a vertical design or a diagonal design depends on the detailed parameters and should be decided on a case by case basis. Another metric $M$ defined as

$$M = \tau_u (1 - \frac{\tau_l}{\tau_{ul}}) z_{ul}^2$$  \hspace{1cm} (1.2)

where $\tau_u$ is the upper laser state lifetime, $\tau_l$ is the lower laser state lifetime, $\tau_{ul}$ and $z_{ul}$ are the intersubband scattering lifetime and the dipole matrix element between the upper laser state and the lower laser state, respectively, is a more appropriate reference when optimizing a QC laser design since it is proportional to the optical gain coefficient.

Fig. 1.2 Schematic of cascaded active regions energetically aligned by an electric field, allowing the electrons to repeat the radiative intersubband transitions.

The loosened transition selection rule in multiple-QW structures offers more design flexibility, e.g., multiple lower laser states (bound-to-continuum) [45] or multiple upper laser states (continuum-to-bound) [46] or both (continuum-to-continuum) [47] can be employed in QC laser band-structure designs to provide a broader optical gain spectrum.
1.2.2 Injectors and electron transport

After electrons make transitions from the upper laser state to the lower laser state and are subsequently scattered to the ground state, they are still in the conduction band so that it is relatively easy to bring them back to the upper laser state in another period of the active region and allow them to repeat the whole process as shown in Fig. 1.2. What needs to be done include (1) placing the upper laser state in the next period active region energetically near the ground state in the first one, and (2) constructing a “bridge” between these two states so that electrons can transport from one to the other. By applying an external electric field perpendicular to the QWs, the spatially separated active regions can energetically align according to (1). Thanks to the flexibility offered by band-structure engineering, a natural choice of the bridges for electrons is another semiconductor multi-QW structure or a superlattice structure. Most QC laser designs employ such a structure for bridging neighboring active regions and facilitating electron transport, and this structure is named “injector”.

Fig. 1.3 (a) Band-structure of a schematic QC laser injector at zero external electric field. (b) Band-structure of this QC laser injector at designed operating electric field. (c) Formation of a miniband of injector states in this QC laser injector at designed operating electric field.
The band-structure of a schematic QC laser injector design is shown in Fig. 1.3. The injector has a superlattice-like structure with 6 pairs of well/barrier material layers. The thicknesses of the well material layers decrease from left to right while the thicknesses of the barrier materials increase. If we calculate the energy levels in each QW assuming they are isolated, at zero electric field, the ground states in all the QW form a “staircase” going up in energy (Fig. 1.3(a)), therefore electrons cannot transport from left to right. However, if we apply an appropriate external electric field pointing left, all the ground states can be brought to a flat-band condition so that electrons are free to the cross the injector (Fig. 1.3(b)). When taking into account the coupling between the QWs, these ground states form a miniband in the entire superlattice like structure which supports fast electron transport (Fig. 1.3(c)). With the flexibility of band-structure engineering, such an operating electric field can be designed to coincide with the electric field required to align two successive active regions according to the scheme in Fig. 1.2. Therefore, when physically connecting active regions with injectors and repeating like a chain, a QC laser is constructed in which electrons can undergo subsequent radiative intersubband transitions in each period.

Fig 1.4 Band-structure of a typical QC laser.
An example of a typical QC laser band-structure is given in Fig. 1.4. Electrons transport from the lower laser state (2) across the miniband in the injector to the upper laser state in the downstream active region (3) through a combination of various scattering processes (mainly LO-phonon scattering or interface roughness induced scattering) and resonant tunneling. The details of different injector designs vary significantly, however, a thick barrier is usually employed in conventional QC laser designs to separate the injector and its downstream active region, mainly in order to achieve selective injection of electrons onto the upper laser state through resonant tunneling [44].

The injector ground state (1) of the design in Fig. 1.4 has an energy separation of more than two LO-phonons from the lower laser state (2), and this is true for most reported QC laser designs. There is a good reason for designing such a large energy separation between the two levels which is called “energy defect” since it does not contribute to the radiative transition: to reduce the thermal backfilling of electrons from the injector ground state to the lower laser state of the preceding active region at high operating temperatures (e.g. room temperature), which would otherwise deteriorate the population inversion and high temperature operation of the QC lasers.

1.2.3 Waveguide and laser cavity

A typical QC laser active core comprises 20 to 50 periods of active region/injector pairs with a total thickness of about 1 to 2 µm. However, the emission wavelength of mid-IR QC lasers ranges from 4 to 20 µm, therefore in the direction perpendicular to the semiconductor layers, the active core itself is not sufficient for good mode confinement (especially for operating wavelengths > 6 µm) which is critical for achieving low threshold current density and high performance. Additional low-loss waveguide structures need to be employed. For QC lasers based on the InGaAs/AlInAs on InP material system, which is the most developed material system for mid-IR QC lasers, the active core is usually sandwiched between low doped InP or AlInAs waveguide cladding layers to achieve
relatively high refractive index contrast, a high mode confinement factor as well as low waveguide loss. An example of the waveguide structure for a QC laser is given in Fig. 1.5.

![Waveguide structure for a typical QC laser](image)

**Fig. 1.5** Waveguide structure for a typical QC laser with ~4.5 µm emission wavelength. The refractive indices for individual material layers and the waveguide mode profile are also plotted. The mode confinement factor is ~0.7.

An important parameter associated with the waveguide structure of a QC laser is the mode confinement factor \( \Gamma \) defined as

\[
\Gamma = \frac{\int_{0}^{L_{ac}} I(z) \, dz}{\int_{-\infty}^{\infty} I(z) \, dz},
\]

where \( I(z) \) is the intensity profile of the optical field along the direction perpendicular to the material layers (denoted as the \( z \) direction), the origin of the \( z \)-axis is set to be at the lower boundary of the laser active core, and \( L_{ac} \) is the thickness of the laser active core. The mode confinement factor characterizes the fraction of the optical field overlapping with the laser active core in which the optical gain medium is present. It has an essential role in determining the laser threshold.
A photon from an intersubband transition is confined and guided within the waveguide structure, which in turn generates more identical photons through stimulated emission, especially when population inversion is achieved. In order to sustain such a process to achieve high coherence in all the emitted photons and overcome all losses, i.e., a laser, a laser cavity needs to be employed to provide coherent optical feedback. One of the simplest type of laser cavities is a Fabry-Perot (FP) resonator which consists of a pair of parallelly opposing mirrors that reflect the photons back and forth within a confined region where the gain medium is present to enhance the stimulated emission (Fig. 1.6(a)). For semiconductor lasers such as QC lasers, a FP resonator can be constructed with a ridge structure as the waveguide for confining the photons in two dimensions, and an as-cleaved crystal plane (facet) at each end of the ridge waveguide as the partial reflecting mirror of the FP laser cavity (Fig. 1.6(b)). Such a FP cavity supports many cavity modes without discrimination within the optical gain spectrum, and the distance between neighboring FP modes, i.e. the free spectral range (FSR), is typically much smaller than the optical gain spectrum width, therefore QC lasers employing...
a FP cavity generally operate with multiple modes. To achieve single-mode operation, other types of laser cavity need to be applied. This is also one of the central topics of this thesis.

1.2.4 QC laser fabrication

The QC laser fabrication processes turn a QC laser design into a functioning physical device and include three major steps: (1) the growth of the QC structure on a substrate wafer, (2) the micro-fabrication of the waveguide/cavity structures and the metal contact, and (3) the device packaging. All three steps are critical for the performance of the final devices and therefore have attracted extensive efforts on advancing the involved technologies.

The growth of the QC structures is mainly conducted with MBE or MOCVD. Both technologies are capable of growing semiconductor heterostructures atomic layer by atomic layer with high quality, therefore the design of the QC laser active core with hundreds of thin material layers can be realized with high accuracy. The epitaxial growth rate is roughly one atomic layer per second, therefore, an entire typical QC laser structure takes several hours to grow. Although the epitaxial growth can be highly accurate, microscopically it is far from perfect. Interface roughness between different material layers, alloy disorders and crystal defects [48, 49] are essentially unavoidable with the current technologies. They all affect the device performance in certain ways [24, 50-53], and therefore should be properly taken into account when designing QC lasers.

The micro-fabrication of the waveguide structures for QC lasers is similar to those for diode lasers which have been developed for decades. Take the fabrication of the simple ridge FP cavity for example, the structuring of the ridge can be achieved with a combination of photolithography and wet or dry chemical etching. Silicon dioxide or silicon nitride is usually used as the electrical insulation material and can be deposited with plasma-enhanced chemical vapor deposition. Alternatively, a buried heterostructure device configuration can be implemented by regrowing insulating InP material to cover the structured ridge waveguide, which also facilitates heat removal from the laser core. The metal contacts can be applied to the structure through either evaporation or sputtering. Electro-plated
top metal contacts with much larger thickness can also be exploited for better heat removal. More advanced fabrication technologies such as electron-beam lithography and etching or focused ion beam etching can be used to create Bragg gratings on the waveguide for wavelength selectivity.

After realization of the waveguide structures and the metal contacts, laser facets are usually formed in the cleaving process. High-reflection (HR) or anti-reflection (AR) coatings may be applied to the laser facets for performance optimization. The laser chips are usually mounted on a heatsink for better heat removal as well as for easy handling since the chips are small and fragile. The laser performance, especially when operated in CW mode at high temperatures, is critically dependent on the technique and quality of the mounting. In order to achieve better high-temperature CW performance, the laser chips are often mounted epitaxial side down (which is much more challenging than epitaxial side up mounting) for faster heat removal, and heat-spreaders made from materials with high thermal conductivity, such as diamond, are commonly used.

The entire fabrication processes for simple ridge waveguide FP cavity QC lasers are summarized in the flow chart in Fig. 1.7.
1.3 State-of-the-art development of mid-IR QC lasers

Ever since the initial demonstration in 1994, QC lasers have drawn much attention from a wide range of fields in academia, industry and the government. Research on QC lasers has undergone rapid progress and efforts on improving QC laser technology in various aspects are still growing. Research on the QC laser device level can roughly be categorized into three major directions. The first major direction is to improve the power performance of the devices, the second one is to advance their spectral characteristics, and the third one is to expand the available wavelength range.

Here, the power performance mainly refers to specifications such as the threshold current density, the output optical power and the power conversion efficiency, or in another word, the wall-plug efficiency (WPE) of the QC lasers. Different approaches have been extensively investigated to improve the QC laser power performance in all these aspects. Exploration of novel active core design strategies, a focus of this thesis, have led to demonstration of high WPE up to ~50% in pulsed operation at cryogenic temperatures [54, 55] and ~23% at room temperature [47], significant steps forward. Different laser cavity structures such as tapered cavities have been studied for enabling high output peak power [56]. Material growth processes have been studied systematically to find the optimal growth conditions [57]. Advanced laser packaging techniques have also been developed to push the CW high-temperature performance limit [58]. With comprehensive optimizations in all these aspects, WPE of ~27% and ~21% have been achieved in pulsed mode and CW mode, respectively at room temperature [59], and there is no reason to believe the WPE would stop improving.

Advancement of spectral characteristics refers to enabling the QC lasers to operate in single mode and the specifications for such single-mode operation, e.g., the wavelength tuning range, the side mode suppression ratio (SMSR), and the single-mode operating current range, etc. Different types of laser cavities have been implemented for facilitating single-mode operation, including cavities with distributed feedback gratings [39, 40], distributed Bragg reflectors [60], or photonic crystals [61] as well as ultra-short cavities [62] and external cavity configurations [63]. Using single-
mode DFB QC laser arrays, wide wavelength tuning ranges has been achieved [64]. However, external cavity QC lasers still have the highest tunability, and in combination with broad optical gain spectra designs, extremely broad wavelength tuning ranges have been demonstrated [46, 65].

While the overall performance of QC lasers is improving steadily over the years, the wavelength range covered by QC lasers is also expanding. The difficulty for reaching shorter wavelengths originates from the limited conduction band offset available for accommodating a relatively high-energy intersubband transition. This challenge is being tackled with unconventional active core designs [66] and different material systems [67]. Limiting our discussion in the mid-IR wavelength range only (excluding THz QC lasers), the difficulty for reaching longer wavelength stems from the much higher waveguide loss, the degradation of population inversion due to shorter upper laser state lifetime, and the lower transverse mode confinement factor. Improvements in the long wavelength range have been gained with optimizations of active core designs [68, 69], waveguide structures [70] and fabrication techniques.

This kind of persistent and vigorous development of QC lasers over the past almost two decades has been seen in many other successful technologies which have made huge impacts on the human society, such as integrated circuits, fiber-optic communications, etc. The same could become true for QC lasers, for their advantages make them suitable candidates for many different crucial applications in various fronts of the society.

1.4 Applications of mid-IR QC lasers

The mid-IR wavelength range is highly important largely for two reasons. First, most molecules in gaseous phase have their fundamental and hence the strongest vibrational and/or rotational-vibrational absorption lines within the mid-IR wavelength range. Second, two atmospheric windows (3-5 µm and 8-14 µm) which allow long-distance transmission of light at the appropriate wavelengths are present within the mid-IR wavelength range. Thanks to these two aspects, the mid-IR
wavelength range is exceptionally attractive for many important applications, such as absorption spectroscopy-based molecular sensing, free space optical communication or IR countermeasures, and thus high performance mid-IR light sources are of crucial technological importance. As compact, powerful and reliable semiconductor lasers, QC lasers are able to cover almost the entire mid-IR wavelength range and have distinct advantages over other mid-IR lasers such as lead salt lasers or solid-state lasers. Therefore, mid-IR QC lasers are the most suitable candidates for light sources employed in these applications.

Absorption-spectroscopy-based molecular sensing is one key application for QC lasers. Extremely high sensitivity (ppt level) can be achieved in light of the strong molecular absorption lines and the sufficient power level available from QC lasers. Multi-species detection with a single light source is made available due to the wide tuning range of QC lasers. Such QC laser based molecular sensing technology can be employed in various fields including air pollutant and greenhouse gas monitoring [71], breath analysis for medical diagnostics [72], non-invasive glucose monitoring [73], explosive and hazardous materials detection [74], industrial process monitoring [75], etc. However, most of the sensing applications require the QC lasers to operate in single mode.

For high power QC lasers operating in the atmospheric windows, besides free space communication [76], they can also be employed in mid-IR LIDAR systems [77] for remote sensing or IR countermeasure systems. On the other hand, high power QC lasers operating in the water absorption band can be used to conduct surgery on the cornea with minimal damage to the other parts of the eye (such as the retina) due to the light’s small penetration depth into tissue.

In short, mid-IR QC lasers have a wide range of potential applications with significant technological advantages. However, in order to implement these applications on large commercial scales, QC laser based systems need to meet certain requirements such as being compact, portable, power-efficient, inexpensive, etc. As the core of the systems, the QC lasers also need to satisfy certain specifications, e.g., high power-efficiency, high operating temperature, low-cost, and for many
applications single-mode operation. The current QC laser technology does not yet fully meet all these requirements. This thesis aims at advancing QC laser technology in all these aspects.

1.5 Thesis organization

Following the brief review of the history, the fundamentals, the recent developments and potential applications of QC lasers, the remainder of this thesis is divided into two main sections.

Chapters 2–3 focus on improving the power performance of QC lasers. Chapter 2 first describes our demonstration of highly power-efficient QC lasers with a novel active core design strategy, the ultra-strong coupling strategy [78]. As a result of the ultra-strong coupling between the injector ground state and the upper laser state, the electron transport is dramatically improved which in turn benefits the slope efficiency and the WPE of the devices. A major step forward in QC laser WPE is achieved from ~34% to 50% [78]. Then a broad-band optical gain QC laser design employing both ultra-strong coupling and short injector design strategies is presented. The width of the optical gain spectrum reaches more than 40% of the transition energy at room temperature. In addition, design strategies such as employing taller electron exit barriers and larger energy defects for improving the temperature characteristics of the ultra-strong coupling QC lasers are explored. In Chapter 3, our proof-of-concept work on building a mid-IR LIDAR system with a high performance ultra-strong coupling QC lasers is discussed [77].

Chapters 4-5 compose the second major section which focuses on achieving single-mode QC lasers cost-effectively with novel laser cavity designs. Chapter 4 describes the realization of single-mode QC lasers with various monolithic coupled-cavities, including hair-pin shaped [79] and candy-cane shaped [80] monolithic coupled-cavities. Such laser cavities make use of the transverse mode mismatch and the resulting reflection of light at the geometrical boundary between a straight waveguide and a curved waveguide with high curvature, which together naturally form a coupled-cavity configuration. Chapter 5 presents a fundamentally different laser cavity design which exploits
the wavelength selectivity associated with a significantly asymmetric Mach-Zehnder interferometer. 
High performance single-mode operation of QC lasers is achieved with FP cavities integrated with such asymmetric Mach-Zehnder interferometers [81]. 

Finally, conclusions on all the work presented are given in Chapter 6, along with an outlook for future development of QC laser related technologies.
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Chapter 2

High-performance Quantum Cascade Lasers
Employing Ultra-strong Coupling Design Strategy

For most QC laser based applications, it is highly desirable that the QC lasers can be operated without complicated and bulky cooling systems while still providing sufficient optical power. The demand on the capacity of the cooling systems mainly depends on the total power consumption of the QC lasers. Therefore, to meet such a goal the QC lasers need to be highly power-efficient, especially for applications where high optical power is another prerequisite. For a real QC laser, its power-efficiency, also known as WPE (acronym for wall-plug efficiency as denoted in Chapter 1), is determined by several factors: the intrinsic characteristics associated with the band-structure [1-3] and the waveguide structure designs [4], the epitaxial growth quality [5], and the quality of device fabrication and packaging processes. The factor associated with the structure designs is of distinctive importance in the sense that it determines the ultimate device performance that can be achieved, and it is expected to have plentiful potential for further improvement. Moreover, it also appears to be an interesting research topic in an academic setting. Therefore, our efforts on advancing the QC laser overall performance with an emphasis on WPE substantially focus on explorations and optimizations from the design perspective.

2.1 WPE of QC lasers

In order to improve the performance of QC lasers, especially the WPE, it is necessary to conduct a thorough study on which crucial device parameters determine the WPE [6,7] and how to further improve them to benefit the WPE. The WPE of a QC laser characterizes the efficiency of the conversion from the device input electric power into its output optical power.
The input electric power \((P_{in})\) equals the product of the input current \((I)\) and the applied voltage \((V)\) across the device:

\[
P_{in} = I \cdot V. \tag{2.1}
\]

The total applied voltage on the device contains two parts:

\[
V = V_{\text{core}} + V_p \tag{2.2}
\]

where \(V_{\text{core}}\) is the voltage applied to the active core of the QC laser, and \(V_p\) is the parasitic voltage drop across the metal contacts and the waveguide cladding layers. If we assume the electric field is uniform across the entire laser active core, then \(V_{\text{core}}\) is the product of the voltage drop across each pair of the active region/injector \((\Delta V)\) and the number of such pairs \((N)\):

\[
V_{\text{core}} = N \cdot \Delta V \tag{2.3}
\]

It can be easily seen from the band-structure of an operating QC laser that \(\Delta V \cdot e\), where \(e\) is the charge of the electron, equals the sum of the photon energy \((E_{\text{ph}})\) and the energy defect \((E_{\text{def}})\), i.e. the energy difference between the lower laser state and the upper laser state in the downstream active region:

\[
\Delta V \cdot e = E_{\text{ph}} + E_{\text{def}}. \tag{2.4}
\]

Both \(E_{\text{ph}}\) and \(E_{\text{def}}\) are determined by the active core design of the QC laser. The parasitic voltage drop \(V_p\) across the metal contacts and the waveguide cladding layers can be characterized by an effective parasitic resistance \(R_p\):

\[
V_p = I \cdot R_p. \tag{2.5}
\]

Therefore, combining Eqns. (2.1)-(2.5), the input electric power \(P_{in}\) can be expressed as

\[
P_{in} = I \cdot \left[ N \left( E_{\text{ph}} + E_{\text{def}} \right)/e + I \cdot R_p \right]. \tag{2.6}
\]

To reveal the key factors for the output optical power of a QC laser \((P_{out})\), we make another assumption that the slope efficiency \((S)\) of the QC laser above the laser threshold current \((I_{th})\) is constant, and therefore when the QC laser is operated above the threshold,

\[
P_{out} = S(I - I_{th}). \tag{2.7}
\]
The remaining task is to write down the laser slope efficiency $S$ in terms of the basic device parameters. The laser slope efficiency, which characterizes the amount of the output optical power increment as a result of a unit input current increment, consists of two factors: (1) the amount of optical power generated within the laser cavity due to a unit input current increment and (2) the fraction of the generated optical power that eventually couples out of the laser cavity. Factor (1) is also known as the internal quantum efficiency ($\eta_{\text{int}}$) and factor (2) is usually called the optical extraction efficiency ($\eta_{\text{extr}}$). The optical extraction efficiency satisfies the expression

$$\eta_{\text{extr}} = \frac{\alpha_m}{\alpha_m + \alpha_w}, \quad (2.8)$$

where $\alpha_w$ is the waveguide loss associated with the laser cavity, and $\alpha_m$ is the mirror loss associated with the facets of the cavity which follows the conventional definition for a FP cavity

$$\alpha_m = -\ln \left( \frac{R_1 R_2}{2 n_{\text{eff}} L} \right), \quad (2.9)$$

where $R_1$ and $R_2$ are the mirror reflectivities for the front-facet and the back-facet, respectively, $n_{\text{eff}}$ is the effective refractive index of the waveguide structure and $L$ is the FP cavity length. The internal quantum efficiency involves more fundamental parameters corresponding to the microscopic processes of the device operation, nevertheless, it can be derived from the rate equations for QC lasers.

For realistic QC lasers, the band-structure for one period of the active region/injector pair typically consists of around 10 or more quantized energy subbands (states) involved in the radiative intersubband transition and the electron transport process, a large fraction of which are within the injector miniband. One can write down the rate equations for all the relevant states and take into account all the possible transitions. Such a set of rate equations is conceivably rather complicated. However, for all the different states in the injector miniband, the details of the interactions among themselves are not of particular interest for analyzing the radiative transition, therefore, when deriving parameters such as the internal quantum efficiency of a QC laser, the entire injector miniband can be treated as a single virtual state with corresponding effective transition lifetimes to
account for its interactions with other states. In fact, the model for the band-structure of a QC laser can be further simplified by treating all the states between the lower laser state and the upper laser state in the downstream active region as one equivalent state without loss of accuracy for predicting the properties of the radiative process, such as the optical gain or the internal quantum efficiency. In this way, a periodic three-level laser system model describing a typical QC laser is constructed as illustrated in Fig. 2.1.

Fig. 2.1 Schematic of the periodic 3-level laser system model for describing a typical QC laser. Level 3 is the upper laser state, level 2 is the lower laser state, and level 1 is the equivalent injector state (level 1’ is the equivalent injector state from the previous period). This model also assumes that non-radiative transitions take place between the following states: 3→2 with transition lifetime $\tau_{32}$, 3→1 with transition lifetime $\tau_{31}$ (the upper laser state lifetime due to non-radiative relaxations is therefore $\tau_3 = \tau_{32}\tau_{31}/(\tau_{32} + \tau_{31})$), 2→1 with transition lifetime $\tau_2$, 1→3 in the downstream active region with transition lifetime $\tau_{inj}$. The photon flux in the cavity is $\Phi$.

For a QC design laser with $N$ stages of active region/injector pairs and an active core mode confinement factor of $\Gamma$, we can further assume each stage has an average mode confinement factor $\Gamma/N$, which would be a good approximation when the thickness of the active core is smaller than or
comparable to the wavelength. Based on the above 3-level laser system model and neglecting the
influence from the environmental temperature, the rate equations for the electron populations in one
period of active region/injector pair read:

\[
\frac{dN_3}{dt} = \frac{N_3}{\tau_{inj}} - \frac{N_3}{\tau_3} - \left( N_3 - N_2 \right) \cdot \frac{\sigma}{N} \cdot \Phi , \tag{2.10}
\]

\[
\frac{dN_2}{dt} = \frac{N_2}{\tau_{32}} - \frac{N_2}{\tau_2} + \left( N_3 - N_2 \right) \cdot \frac{\sigma}{N} \cdot \Phi , \tag{2.11}
\]

\[
\frac{dN_1}{dt} = \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_2} - \frac{N_1}{\tau_{inj}} , \tag{2.12}
\]

where \( N_1, N_2 \) and \( N_3 \) are the electron populations on the states 1, 2 and 3, respectively, \( \sigma \) is the
transition crosssection associated with the radiative intersubband transition between state 3 and state 2,
all the lifetimes are explained in Fig. 2.1, and \( \Phi \) is the photon flux in the cavity, and is given by

\[
\Phi = \frac{N_{ph}}{V_{ph}c} , \tag{2.13}
\]

where \( N_{ph} \) is the total number of photons in the cavity, \( V_{ph} \) is the mode volume of the photons, and \( c \) is
the speed of light in the laser waveguide. In addition we have the conservation of total electron
population

\[
N_1 + N_2 + N_3 = N_{total} , \tag{2.14}
\]

where \( N_{total} \) is the total electron population for one stage of active region/injector pair. The rate
equation for the photon population is given by:

\[
\frac{dN_{ph}}{dt} = N(N_3 - N_2) \cdot \frac{\sigma}{N} \cdot \Phi - \frac{N_{ph}}{\tau_{ph}} , \tag{2.15}
\]

where \( \tau_{ph} \) is the photon lifetime associated with the cavity. To find the steady state solution for the
above rate equations, one can set \( dN_1/dt, dN_2/dt, dN_3/dt \) and \( dN_{ph}/dt \) in Eqns. (2.10)-(2.12) and
(2.15) all to be zero and solve for the desired parameters:

\[
\frac{N_1}{\tau_{inj}} - \frac{N_3}{\tau_3} - \left( N_3 - N_2 \right) \cdot \frac{\sigma}{N} \cdot \Phi = 0 , \tag{2.16}
\]

\[
\frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_2} + \left( N_3 - N_2 \right) \cdot \frac{\sigma}{N} \cdot \Phi = 0 , \tag{2.17}
\]
\[
\frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_2} - \frac{N_1}{\tau_{inj}} = 0, \quad (2.18)
\]
\[
(N_3 - N_2) \cdot \sigma \cdot \Gamma \cdot \Phi - \frac{N_{ph}}{\tau_{ph}} = 0. \quad (2.19)
\]

Also we notice that in the above equations, \(N_1\) only appears in the form of \(N_1/\tau_{inj}\) which corresponds to the current flowing through the structure
\[
I = \frac{eN_1}{\tau_{inj}}. \quad (2.20)
\]

Therefore, from Eqns. (2.16)-(2.20) and with the help of Eqn. (2.13) we can find the steady state solution for \(N_{ph}\) in terms of current \(I\) to be
\[
\frac{N_{ph}}{\tau_{ph}} = N \frac{\tau_{32}\tau_3 - \tau_2\tau_3}{\tau_{32}\tau_3 - \tau_2\tau_3 + \tau_3\tau_2} \cdot \frac{I}{e} - N \frac{\tau_{31}V_{ph}}{\tau_3\tau_{ph}(\tau_{31} + \tau_2) \sigma \Gamma}. \quad (2.21)
\]

The term \(N_{ph}/\tau_{ph}\) in Eqn. (2.21) characterizes the number of photons lost within the cavity per unit time, which also equals the number of photons generated per unit time. Therefore the internal efficiency is derived as:
\[
\eta_{int} = \frac{dP_{gen}}{dl} = \frac{d(N_{ph}E_{ph}/\tau_{ph})}{dl} = N \frac{\tau_{32}\tau_3 - \tau_2\tau_3}{\tau_{32}\tau_3 - \tau_2\tau_3 + \tau_3\tau_2} \cdot \frac{E_{ph}}{e}, \quad (2.22)
\]

where \(P_{gen}\) denotes the total optical power generated within the cavity. The expression on the right hand side of Eqn. (2.22) can be rearranged as
\[
\eta_{int} = N \frac{\tau_{32}\tau_3 - \tau_2\tau_3}{\tau_{32}\tau_3 - \tau_2\tau_3 + \tau_3\tau_2} \cdot \frac{E_{ph}}{e} = N \frac{\tau_{eff}}{\tau_{eff} + \tau_3} \cdot \frac{E_{ph}}{e}, \quad (2.23)
\]

where \(\tau_{eff}\) is defined as
\[
\tau_{eff} = \tau_3(1 - \frac{\tau_2}{\tau_{32}}). \quad (2.24)
\]

The above expression for \(\eta_{int}\) allows one to estimate the output optical power with Eqn. (2.7).

However, the model of the QC laser shown in Fig. 2.1 is rather idealized, because it assumes all the electrons from the injector are eventually injected onto the upper laser state, which can be quite different from reality. Besides being injected into the upper laser state, the electrons from the injector can also go through various leakage paths, such as being injected into the states above the upper laser state and subsequently relaxing down to the lower laser state, directly relaxing down to the lower
laser state, or escaping into the continuum states via thermal excitation, etc. All of these leakage paths of electron transport contribute to the current flow through the structure but bypass the radiative transition, and thus lower the slope efficiency. In order to obtain a more accurate estimation of the slope efficiency, an important modification which takes into account the percentage of the electrons from the injector injected onto the upper laser state should be included in the internal quantum efficiency expression for QC lasers. This percentage is referred to as the electron injection efficiency \( \eta_{inj} \) here, and the modified internal quantum efficiency expression is then

\[
\eta_{int} = \eta_{inj} \cdot N \frac{\tau_{32} \tau_3 - \tau_{23} \tau_2}{\tau_{32} \tau_2 + \tau_{23} \tau_3} \cdot \frac{E_{ph}}{e} = \eta_{inj} \cdot N \frac{\tau_{eff}}{\tau_{eff} + \tau_2} \cdot \frac{E_{ph}}{e}.
\]  

(2.25)

The slope efficiency \( S \) now reads

\[
S = \eta_{extr} \eta_{int} = \frac{\alpha_m}{\alpha_m + \alpha_w} \cdot \eta_{inj} \cdot N \frac{\tau_{eff}}{\tau_{eff} + \tau_2} \cdot \frac{E_{ph}}{e},
\]  

(2.26)

where \( \eta_{extr} \) is given in Eqn. (2.8).

We now have all the components for the WPE calculation. The output optical power \( P_{out} \) can be expressed as

\[
P_{out} = S(I - I_{th}) = \frac{\alpha_m}{\alpha_m + \alpha_w} \cdot \eta_{inj} \cdot N \frac{\tau_{eff}}{\tau_{eff} + \tau_2} \cdot \frac{E_{ph}}{e} \cdot (I - I_{th}),
\]  

(2.27)

and finally the WPE reads

\[
\text{WPE} = \frac{P_{out}}{P_{in}} = \frac{\alpha_m}{\alpha_m + \alpha_w} \cdot \eta_{inj} \cdot N \frac{\tau_{eff}}{\tau_{eff} + \tau_2} \cdot \frac{E_{ph}}{e} \cdot (I - I_{th}) \cdot \frac{1}{N(E_{ph} + E_{def})/e + l \cdot R_p}.
\]  

(2.28)

However, Eqn. (2.28) is a rather complicated expression for the WPE. With some rearrangement of the terms, the meaning of Eqn. (2.28) becomes more comprehensible:

\[
\text{WPE} = \left[ \frac{E_{ph}}{E_{ph} + E_{def} + e l \cdot R_p / N} \right] \cdot \left[ \frac{l - I_{th}}{I} \right] \cdot \left[ \eta_{inj} \cdot \frac{\tau_{eff}}{\tau_{eff} + \tau_2} \right] \cdot \left[ \frac{\alpha_m}{\alpha_m + \alpha_w} \right],
\]  

(2.29)

where the expressions in the four square brackets are denoted from left to right as the voltage efficiency, the current efficiency, the internal efficiency, and the optical extraction efficiency. The underlying physical meanings of the above individual efficiencies are palpable. The voltage efficiency reflects the fact that not all the voltage drop across the device contributes to the radiative
transitions, the energy defect between the lower laser state and the upper laser state in the next period as well as the parasitic voltage drop on the contacts and waveguide structures lowers the voltage efficiency. The current efficiency states that only the fraction of the current above the laser threshold contributes to the photon generation. The internal efficiency characterizes the probability for the occurrence of a photon emission when an electron transports through one stage of the active region/injector pair when the QC laser is operated above the threshold. The optical extraction efficiency, as explained previously, is the fraction of the generated photons that eventually escape the laser cavity and become utilizable optical power.

The WPE of QC lasers can be improved by improving any of the aforementioned efficiencies. The voltage efficiency can be improved by reducing the energy defect in the band-structure design [8], however, an insufficient energy defect would not effectively suppress the thermal backfilling effect at high operating temperatures and/or in CW operation, so the potential for improvement is rather limited. The optical collection efficiency can be improved by reducing the waveguide loss which also benefits the current efficiency, or increasing the mirror loss through tailoring the cavity length or applying anti-reflection coatings. However, increasing the mirror loss also degrades the threshold current density and the current efficiency, therefore, the mirror loss should be optimized in order to maximize the WPE [9].

The internal efficiency and the current efficiency are highly dependent on the band-structure determined parameters of the QC lasers. The internal efficiency can be increased by either optimizing the $\tau_{\text{eff}}/(\tau_{\text{eff}} + \tau_2)$ term or improving the electron injection efficiency $\eta_{\text{inj}}$, both of which are closely related to the band-structure and readily adjustable by design.

The term $\tau_{\text{eff}}/(\tau_{\text{eff}} + \tau_2)$ can be improved by increasing the relaxation lifetimes associated with the upper laser state ($\tau_{32}, \tau_{31}, \tau_3$) and/or reducing the relaxation lifetime associated with the lower laser state ($\tau_2$). Making the radiative transition more diagonal decreases the spatial overlap of the upper laser state with the lower laser state and the other states below, therefore increases the
corresponding relaxation lifetimes ($\tau_{32}, \tau_{31}, \tau_3$). Positioning at least one state at one LO-phonon energy (~34 meV) below the lower laser state helps to depopulate the lower laser state via LO-phonon scattering and reduces $\tau_2$. Meanwhile, both design strategies also benefit the population inversion and as a consequence may decrease the laser threshold current density; however, a more diagonal design may also significantly reduce the dipole moment for the radiative transition and consequently compromise the increased population inversion and reduce the optical gain, and therefore should be carefully employed when designing the band-structure of QC lasers.

Fig. 2.2 Light-current-voltage (LIV) characteristics for a typical QC lasers. The roll-over current (density) is indicated by the red circle on the LI curve.

On the other hand, one way to improve the electron injection efficiency $\eta_{inj}$ is to speed up the electron injection process, i.e. the electron transport through the injector to the upper laser state in the downstream period. As the electron injection into the upper laser state becomes faster, the electron transport through leakage paths becomes less significant, and thus the injection efficiency $\eta_{inj}$ is higher. Faster electron injection not only benefits the internal efficiency, but also improves the current efficiency from two aspects. First of all, a higher $\eta_{inj}$ results in a better population inversion at any given current density and hence lowers the threshold current density. Secondly, a faster electron
transport allows for a larger roll-over current density, i.e. the current density beyond which the output optical power begins to decrease as shown in Fig. 2.2. From the aforementioned steady state rate equations Eqns. (2.16)-(2.19) in combination with Eqns. (2.13)-(2.14), the current through the device structure is derived to be

$$I = \frac{N_1}{\tau_{inj}} = \frac{\tau_{31} + \tau_2}{2\tau_2\tau_{31} + \tau_{inj}} N_{total} - \frac{\tau_{31} - \tau_2}{2\tau_2\tau_{31} + \tau_{inj} + \tau_{inj} \tau_{inj}} \cdot \frac{V_{ph}}{c \tau_{ph} \sigma \Gamma} \approx \frac{1}{2\tau_2 + \tau_{inj}} N_{total} - \frac{1}{2\tau_2 + \tau_{inj}} \cdot \frac{V_{ph}}{c \tau_{ph} \sigma \Gamma} \quad (\text{since } \tau_{31} \gg \tau_2), \quad (2.30)$$

where $\tau_{inj}$ is sensitively dependent on the band-structure configuration strongly influenced by the applied external electric field. The maximum current through the structure is achieved when $\tau_{inj}$ assumes its minimum value under the specific bias condition. Although the peak WPE of a QC laser is usually reached somewhere before the roll-over current density, a larger roll-over current density in general dictates a higher current efficiency that can be achieved. Briefly stated, speeding up the electron transport from the injector ground state to the upper laser state is a key to the laser performance improvements, including lower threshold current density, higher slope efficiency and higher WPE.

### 2.2 Electron transport in QC structures

As briefly discussed in Chapter 1, the electron transport from the lower laser state through the whole injector to the upper laser state in the next stage occurs mainly via a combination of phonon-assisted scattering [10], interface roughness induced scattering [10,11], and resonant tunneling [12].

Among all the phonon-assisted scattering processes, scattering assisted by the emission of LO-phonons which is present at any temperature is the dominant process [10] for intersubband transitions. Among the active region ground states and within the mini-band of the injector states, the LO-phonon-assisted scattering processes undergo multiple paths and are relatively fast with
relaxation times on the order of 0.1 ps [10]; therefore they usually do not form the bottleneck for the electron transport.

The interface roughness refers to the random surface profile of the interface between the two adjacent layers of different materials. Such interface roughness can be seen clearly from the scanning tunneling microscope (STM) image of an InGaAs/AlInAs superlattice structure shown in Fig. 2.3. The profile of the interface roughness in the direction perpendicular to the material layers $h(\vec{r})$ is usually modeled as a random function with a Gaussian autocorrelation function [13]:

$$\int h(\vec{r})h(\vec{r} - \vec{r}_1) d\vec{r} = \Delta^2 e^{-|\vec{r}_1|^2 / \Lambda^2} ,$$  \hspace{1cm} (2.31)

where $\vec{r}$ and $\vec{r}_1$ are vectors within the nominal interface between the two layers, $\Delta$ is the mean square roughness height, and $\Lambda$ is the correlation length. Although the device structures are essentially grown atomic layer by atomic layer, the interface roughness cannot be eliminated with the current material growth technologies, and the associated parameters ($\Delta$ and $\Lambda$) are critically dependent on the growth conditions [14]. The interface roughness is essentially a perturbation to the bandstructure, and it introduces both intersubband scattering between different quantized subbands and intrasubband scattering within individual quantized subbands, and hence has critical influences on the device operation and performance. Similar to LO-phonon-assisted scattering, the intersubband scattering processes induced by interface roughness directly contribute to the electron transport. The interface roughness induced intersubband scattering is an elastic scattering process, and the scattering rate satisfies the expression [11]:

$$\hbar \tau_{21}^{-1} = \frac{\pi m^*}{\hbar^2} \Delta^2 \Lambda^2 \delta U^2 \sum_i \{ \phi_1(z_i) \phi_2(z_i) \}^2 e^{-\Lambda^2 k_{21}^2 / 4} ,$$  \hspace{1cm} (2.32)

where $m^*$ is the electron effective mass in the quantum well material, $\delta U$ is the band offset associated with the two different materials composing the semiconductor heterostructure, $\phi_1$ and $\phi_2$ are the wavefunctions of the two concerned quantized states, respectively, $z_i$ is the position of the $i_{th}$ interface in the entire structure, and $k_{21}$ is the momentum change associated with the intersubband scattering process as shown in Fig. 2.4. Such interface roughness induced intersubband scattering processes also
take place between multiple pairs of subband states, and estimations of their scattering rates based on conventionally accepted values of the key material parameters (e.g., $\Delta \approx 0.15 \text{ nm}$, $\Lambda \approx 6 \text{ nm}$) have shown that interface roughness induced intersubband scattering rates are comparable to those associated with the LO-phonon assisted scattering [15]. Thus, interface roughness induced intersubband scattering also contributes significantly to the electron depopulation from the lower laser state within the active region as well as the electron transport within the injector.

Fig. 2.3 STM image of a superlattice structure (InGaAs/AlInAs). The interface between neighboring material layers are highlighted in blue. (Courtesy of Mathew Woods, Federico Lopez, Kara Kanedy and Michael Weimer, Texas A&M University.)
Fig. 2.4 Schematic of the interface-roughness-induced elastic intersubband scattering process.

Both the LO-phonon-assisted scattering and the interface-roughness-induced scattering require spatial overlap between the two subband wavefunctions. When the two concerned wavefunctions are relatively spatially separated, such scattering mechanisms are drastically suppressed, and the electron transport between the two subbands mainly relies on resonant tunneling when their energy levels are sufficiently close. In fact, for most conventional QC laser designs, the electron transport from the injector ground state to the upper laser state in the next stage occurs mainly via resonant tunneling because a thick injection barrier (also usually the thickest barrier in the entire structure) is usually employed which spatially separates the downstream active region from the injector. A major advantage of such a resonant tunneling based electron transport process is that it facilitates selective injection of electrons onto the upper laser state. In addition, the last barrier of the active region (exit barrier) is also usually designed to be relatively thick (one benefit for such a band-structure configuration is to have the ground states in the active region sufficiently confined so that electrons can quickly depopulate from the lower laser state to the states below via scattering processes), that electrons transport from the ground state in the active region to the injector states also
via resonant tunneling. Theoretical study on the resonant tunneling of electrons through thick potential barriers suggests that the tunneling rate can be severely suppressed by various mechanisms and consequently become the bottleneck of the electron transport process. On the other hand, the electron transport among injector states may occasionally also rely on resonant tunneling processes, however, since the barriers in the injector are usually much thinner in comparison, such resonant tunneling processes within the injector are less likely to be bottlenecks. Nevertheless, several design strategies have been demonstrated to reduce the electron transport time within the injector, such as the short injector designs [16] and the injectorless designs [17,18], however, they did not focus on optimizing the resonant tunneling process through the thick injection barrier.

The resonant tunneling process is a coherent process, meaning that the phase information of the concerned states influences the transitions and is preserved during the transitions, therefore it should not be treated as a scattering process with an effective lifetime which can be incorporated in rate equations similar to those in the previous section (the phase information is irrelevant in such scattering processes). Instead, such a coherent process can be readily described and studied within the density matrix formalism [19-23]. To study the resonant tunneling process in QC lasers, we can simplify the entire band-structure as a periodic two-level system as shown in Fig. 2.5. Since the most crucial resonant tunneling process in the QC laser operation is the one between the injector ground state and the downstream upper laser state through the thick injection barrier, the simple model illustrated in Fig. 2.5 can be considered as an abstract picture for this critical process with state 1 representing the injector ground state and the state 2 representing the downstream upper laser state.

In this periodic band-structure, the thick injection barriers are treated as the boundaries between individual periods, therefore, states 1 and 2 are not eigenstates of the entire periodic structure, but instead are the localized eigenstates belonging to two different periods, respectively. In reality, when state 1 and state 2 are energetically close to each other under a certain bias electric field range, they will couple together and form a pair of eigenstates associated with the entire periodic structure that extend across both periods, similar to two atoms forming bonds. Such “true” eigenstates of the
entire periodic structure can be constructed as the linear combination of state 1 and state 2 with the tight binding formalism. These true eigenstates have an energy separation between themselves that changes monotonously with the absolute value of the energy detuning between state 1 and state 2 ($\Delta_{1,2}$). The energy separation reaches its minimum value $2|\Omega_{1,2}|$ when $\Delta_{1,2}=0$, where $\Omega_{1,2}$ is defined as the coupling strength between state 1 and state 2 when they are energetically in resonance and is given by

$$\Omega_{1,2} = \langle \phi_1 | \hat{H} | \phi_2 \rangle = \int_{-\infty}^{\infty} \phi_1^* \hat{H} \phi_2 \, dz = \Omega_{2,1}^*,$$

(2.33)

Where $\phi_1$ and $\phi_2$ are the wavefunctions for state 1 and state 2, respectively, and $\hat{H}$ is the Hamiltonian associated with the entire periodic structure.

Fig. 2.5 Schematic of the periodic two-level system model for studying the resonant tunneling process through the thick injection barrier in QC lasers.

In order to study the resonant tunneling process between the injector ground state and the downstream upper laser state in QC lasers based on the simplified system model in Fig. 2.5, we further assume the phenomenological population relaxation time for the upper laser state is $\tau_2$, and the corresponding relaxed electron population all transitions to the injector ground state below. Such a phenomenological relaxation process takes into account various intersubband scattering processes as
well as the stimulated emission when operated above the threshold, while the model remains considerably simple. Furthermore, the dephasing time associated with this coherent process is designated $\tau_{\parallel 1,2}$.

The state of the system is described by the following density matrix

$$\hat{\rho} = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix},$$

(2.34)

where $\rho_{11}$ and $\rho_{22}$ are the probability that the system is in state 1 and state 2, respectively, and $\rho_{12} = \rho_{21}^{*}$ characterizes the coherence between state 1 and state 2. The time evolution of the above density matrix is given by

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar} \left[ \hat{H}, \hat{\rho} \right] = -\frac{i}{\hbar} \left[ \hat{H} \hat{\rho} - \hat{\rho} \hat{H} \right] = -\frac{i}{\hbar} \left[ \begin{pmatrix} \rho_{12} \\ \tau_{\parallel 1,2} \\ \rho_{22} \\ \tau_2 \end{pmatrix}, \begin{pmatrix} \rho_{12} \\ \tau_{\parallel 1,2} \\ \rho_{22} \\ \tau_2 \end{pmatrix} \right],$$

(2.35)

where $\hat{H}$ written in the matrix form is

$$\hat{H} = \begin{pmatrix} E_1 & \Omega_{1,2} \\ \Omega_{2,1} & E_1 + \Delta_{1,2} \end{pmatrix},$$

(2.36)

where $E_1$ is the energy for state 1.

Since we are mostly interested in the steady state solutions for the above density matrix equations, therefore setting Eqn. (2.35) equal to zero and expanding it with Eqn. (2.36), the following independent equations for the density matrix elements are obtained:

$$\frac{i}{\hbar} \left( \rho_{12} \Omega_{2,1} - \rho_{21} \Omega_{1,2} \right) + \frac{\rho_{22}}{\tau_2} = 0,$$

(2.37)

$$\frac{i}{\hbar} \left( \rho_{11} - \rho_{22} \right) \Omega_{1,2} + \frac{i}{\hbar} \rho_{12} \Delta_{1,2} - \frac{\rho_{12}}{\tau_{1,2}} = 0.$$  

(2.38)

Because the system is closed, the total population is conserved, therefore we also have

$$\rho_{11} + \rho_{22} = 1.$$  

(2.39)

From Eqns. (2.37)-(2.39), the steady state solutions for $\rho_{11}$ and $\rho_{22}$ are found to be

$$\rho_{11} = \frac{1 + \Delta_{1,2}^2 \tau_{1,2}^2/\hbar^2 + 2 |\Omega_{1,2}|^2 \tau_{1,2} \tau_2/\hbar^2}{1 + \Delta_{1,2}^2 \tau_{1,2}^2/\hbar^2 + 4 |\Omega_{1,2}|^2 \tau_{1,2} \tau_2/\hbar^2},$$

(2.40)
\[ \rho_{22} = \frac{2|\Omega_{1,2}|^2 \tau_{11,2} \tau_2 / \hbar^2}{1 + \Delta_{1,2}^2 \tau_{11,2} \tau_2 / \hbar^2 + 4|\Omega_{1,2}|^2 \tau_{11,2} \tau_2 / \hbar^2}. \] 

(2.41)

In steady state, the rate of electrons moving from state 1 to state 2 via resonant tunneling should match the rate of electrons scattered out of state 2 due to the continuity of the current density, therefore the resonant tunneling current density through the structure is given by

\[ J_{RT} = \frac{N_2}{\tau_2} = \frac{\rho_{22} N_{total}}{\tau_2} = \frac{N_{total}}{\tau_2} \cdot \frac{2|\Omega_{1,2}|^2 \tau_{11,2} / \hbar^2}{1 + \Delta_{1,2}^2 \tau_{11,2} / \hbar^2 + 4|\Omega_{1,2}|^2 \tau_{11,2} / \hbar^2}. \] 

(2.42)

where \( N_2 \) is the sheet electron density on state 2, and \( N_{total} \) is the total sheet electron density per period of active region/injector pair and is determined by the doping density.

### 2.3 Role of interface roughness in key resonant tunneling processes

According to Eqn. (2.42), the resonant tunneling current density is critically dependent on the dephasing time \( \tau_{11,2} \). For mid-IR QC lasers, the dominant dephasing mechanism (in-plane momentum relaxation) associated with the intersubband transitions is the interface roughness induced intrasubband scattering \([11,24,25]\), while the dephasing also has contributions from all the other scattering processes including LO-phonon scattering, interface roughness induced intersubband scattering, impurity scattering, electron-electron scattering, etc. Such dephasing mechanisms cause linewidth broadening of the associated transitions. Neglecting all the other contributions, the intersubband transition (state 1 \( \rightarrow \) state 2) linewidth broadening associated with the interface roughness induced intrasubband scattering is given by \([20,25]\)

\[ \hbar \tau_{11,2}^{-1} = \frac{\pi m^*}{\hbar^2} \Delta^2 \Lambda^2 \delta U^2 \sum \left\{ \phi_1^2(z_i) - \phi_2^2(z_i) \right\}^2, \] 

(2.43)

where all the parameters are defined as in the previous section. Apparently, the linewidth broadening of different transitions are all different due to the factor \( \sum \left\{ \phi_1^2(z_i) - \phi_2^2(z_i) \right\}^2 \), which can be readily calculated from the band-structure. The linewidth broadening (or equivalently the dephasing time) associated with the resonant tunneling process is difficult to be directly measured, and its estimation requires knowledge on the material parameters including \( \Delta \) and \( \Lambda \) where are also quite
challenging to characterize [26]. Fortunately, the spectra of the spontaneous emission of QC lasers which corresponds to the intersubband transition between the upper laser state and the lower laser state can be easily measured, and the factor $\frac{\pi m^*}{\hbar^2}\Delta^2\Lambda^2\delta U^2$ can be extracted from its linewidth and the calculation of its wavefunction factor. With such a result, the linewidth of all the other intersubband transitions can be estimated.

When carrying out such linewidth estimation, one usually finds that the broadening associated with the resonant tunneling between the injector ground state and the downstream upper laser state is much larger than that of the spontaneous emission. This is mainly due to the difference in the $\sum_i\left(\phi_1^2(z_i) - \phi_2^2(z_i)\right)^2$ factors: for the spontaneous emission, the upper laser state and the lower laser state have significant spatial overlap at the interfaces within the active region, therefore $\phi_1^2(z_i)$ and $\phi_2^2(z_i)$ cancel each other and $\left(\phi_1^2(z_i) - \phi_2^2(z_i)\right)^2$ is relatively small; on the other hand, for the resonant tunneling process, the injector ground state and the downstream upper laser state have little spatial overlap at the interfaces where either wavefunction is present, therefore $\left(\phi_1^2(z_i) - \phi_2^2(z_i)\right)^2$ is relative large. Such an observation can also be understood intuitively from the following picture. The interface roughness induced broadening to the intersubband transitions originates from the shifting of the energy levels of the states involved as a result of the fluctuations of the quantum wells’ thicknesses introduced by the interface roughness. Therefore, if the two states are spatially located in the same region, then the fluctuation of the quantum wells’ thicknesses shift their energy levels in the same direction, and the transition energy changes significantly less; however, if the two states are spatially located in different regions, then the fluctuation of the quantum wells’ thicknesses shift their energy levels in uncorrelated directions, and the transition energy changes significantly more, leading to much larger broadening.
2.4 Optimization of the coupling strength

The broadening associated with the resonant tunneling between the injector ground state and the downstream upper laser state is usually a few times larger than that of the spontaneous emission. For QC lasers operating around the 4 µm to 5 µm range, the full width at half maximum (FWHM) of the spontaneous emission spectrum is typically ~25 meV, which suggests the broadening of the resonant tunneling process is on the order of 100 meV, corresponding to a dephasing time of a few femtoseconds (~5 fs would be a reasonable estimation for $\tau_{\parallel 1,2}$). For such short dephasing time which is mostly determined by the material growth technology and therefore difficult to change, the resonant tunneling current density described by Eqn. (2.42) can be severely limited. However, it is possible to overcome such negative effect of the fast dephasing process from the band-structure design perspective. An effective way is to increase the coupling strength between the injector ground state and the downstream upper laser state since $J_{RT}$ increases monotonously with $|\Omega_{1,2}|^2$. Without loss of generality, we can focus on the resonant tunneling current density when the two states are in full resonance, i.e. $\Delta_{1,2} = 0$, and Eqn. (2.42) becomes

$$J_{RT, max} = \bar{N}_{total} \cdot \frac{2|\Omega_{1,2}|^2 \tau_{\parallel 1,2}/\hbar^2}{1+4|\Omega_{1,2}|^2 \tau_{\parallel 1,2}\tau_2/\hbar^2}$$  \hspace{1cm} (2.44)

where $J_{RT, max}$ is the maximum current density that can be supported by this resonant tunneling process. According to Eqn. (2.44) $J_{RT, max}$ increases when the coupling strength $|\Omega_{1,2}|$ becomes larger, but eventually when $4|\Omega_{1,2}|^2 \tau_{\parallel 1,2}\tau_2 \gg \hbar^2$, $J_{RT, max}$ saturates at $\bar{N}_{total} \tau_2$, which is no longer limited by the resonant tunneling process but by the upper laser state lifetime, and this is referred to as the strong coupling regime [12]. Further increase of $|\Omega_{1,2}|$ no longer benefits the resonant tunneling current density, however, it increases the energy splitting (equals $2|\Omega_{1,2}|$) between the pair of extended eigenstates formed by the localized in-resonance states. In the picture of extended eigenstates, both eigenstates contribute to the optical gain, therefore a larger energy splitting between them leads to a broader optical gain spectrum and a lower peak gain coefficient, which is harmful for the laser...
threshold performance. These facts suggest there is a trade-off between the resonant tunneling current density and the gain profile, and the coupling strength within an optimal range should be employed to optimize the laser overall performance.

In most conventional designs, the employed coupling strength between the injector ground state and the downstream upper laser state was in the range from 2 meV to 4 meV, and such a coupling strength was prevalently believed to be just entering the strong coupling regime and thus the resonant tunneling current density was optimized. On the other hand, since the energy splitting between the anti-crossed states is significantly smaller than the broadening of the energy level of individual states, quite conveniently, the optical gain profile is also well maintained in this way. This seems to be a satisfying solution to the task of coupling strength optimization. However, an oversimplified assumption made to estimate the commencement of the strong coupling regime was long neglected: the dephasing time (or equivalently the transition linewidth broadening) associated with the resonant tunneling process was assumed to be identical to that of the spontaneous emission. For example, the optical gain spectrum width for QC lasers operating around 4 µm to 5 µm range is around 25 meV, corresponding to a dephasing time of ~25 fs. The typical value for the upper laser state lifetime is ~5 ps. Therefore, in order to achieve the strong coupling regime $4\left|\Omega_{1,2}\right|^2\tau_{\parallel,1,2}\tau_2 \gg \hbar^2$ dictates that $\left|\Omega_{1,2}\right| \gg 1$ meV, and $\left|\Omega_{1,2}\right| \sim 3$ meV would be sufficient for the QC laser to operate in the strong coupling regime. However, from Eqn. (2.43) we know that the dephasing time associated with the resonant tunneling process is actually much smaller, therefore the coupling strength employed in most conventional designs is not sufficient to overcome such fast dephasing process and reach the strong coupling regime. Intuitively, the straightforward solution is to further increase the coupling strength. If the dephasing time of the resonant tunneling process is a quarter of that of the spontaneous emission, then the coupling strength should approximately be doubled.

Nevertheless, a more comprehensive density matrix based model was developed to investigate this issue and pinpoint the optimal range for the coupling strength [20]. This model is
based on a periodic three-level system which includes the injector state (1), the upper laser state (3) and the lower laser state (2) in one QC laser stage confined by the injection barriers as shown in Fig. 2.6. The model presented below is similar to that in [20] and it takes into account the dephasing times for the transitions between each pair of states \((\tau_{\|1,2}, \tau_{\|1,3}, \text{and} \tau_{\|2,3})\) respectively and the scattering relaxation time between state 3 and state 2 \((\tau_3)\) as well as that between state 2 and state 1 \((\tau_2)\), however, the thermal backfilling term is not included. Defining the upper laser state 3 to be at the zero energy level, the time evolution equations of the density matrix is given by

\[
\frac{d}{dt} \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} \\ \rho_{21} & \rho_{22} & \rho_{23} \\ \rho_{31} & \rho_{32} & \rho_{33} \end{pmatrix} = \frac{i}{\hbar} \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} \\ \rho_{21} & \rho_{22} & \rho_{23} \\ \rho_{31} & \rho_{32} & \rho_{33} \end{pmatrix} \begin{pmatrix} -\delta_{1,3} & 0 & \Omega_{1,3} \\ 0 & -(\hbar \omega + \Delta_{3,2}) & 0 \\ \Omega_{3,1} & \Omega_{1,3} \exp(i \omega t) & 0 \end{pmatrix} \]

\[= \begin{pmatrix} -\rho_{22} \tau_2^{-1} & \rho_{12} \tau_{\|1,2}^{-1} & \rho_{13} \tau_{\|1,3}^{-1} \\ \rho_{21} \tau_{\|1,2}^{-1} & \rho_{22} \tau_2^{-1} - \rho_{33} \tau_3^{-1} & \rho_{23} \tau_{\|2,3}^{-1} \\ \rho_{31} \tau_{\|1,3}^{-1} & \rho_{32} \tau_{\|2,3}^{-1} & \rho_{33} \tau_3^{-1} \end{pmatrix}, \quad (2.45)\]

where \(\Omega_l\) is the Rabi frequency associated with the optical field and is defined as (in the unit of energy)

\[
\Omega_l = 2e |z_{32}| \cdot |E|, \quad (2.46)\]

where \(E\) is the electric component of the optical field, and \(z_{32}\) is the dipole moment associated with the intersubband transition from state 3 to state 2 and is given by

\[
z_{32} = \int_{-\infty}^{\infty} \phi_3^* z \phi_2 dz. \quad (2.47)\]
Again, we have conservation of the total electron population on the three subbands
\[ \rho_{11} + \rho_{22} + \rho_{33} = 1. \]  
(2.48)

From Eqn. (2.45) we see that the coherence terms \( \rho_{32}, \rho_{23}, \rho_{21}, \rho_{12} \) is driven by the fast changing optical field \( \Omega_l \exp(-i\omega t) \) or \( \Omega_l \exp(i\omega t) \), therefore when the photon energy \( \hbar\omega \) is close to the transition energy between state 3 and state 2, and the detuning \( \delta_{1,3} \) between state 1’ and state 3 is small, we expect the coherence terms \( \rho_{32}, \rho_{23}, \rho_{21}, \rho_{12} \) to oscillate in the same frequency \( \omega \) as the optical field, and the corresponding solutions of Eqn. (2.45) should have the form:
\[ \rho_{23} = \bar{\rho}_{23}\exp(i\omega t), \]  
(2.49a)
\[ \rho_{32} = \bar{\rho}_{32}\exp(-i\omega t), \]  
(2.49b)
\[ \rho_{21} = \bar{\rho}_{21}\exp(i\omega t), \]  
(2.49c)
\[ \rho_{12} = \bar{\rho}_{12}\exp(-i\omega t), \]  
(2.49d)

where \( \bar{\rho}_{23}, \bar{\rho}_{32}, \bar{\rho}_{21}, \bar{\rho}_{12} \) have much slower time evolution than \( \exp(\mp i\omega t) \). If we substitute Eqn. (2.49) into Eqn. (2.45), then after rearrangement it becomes
\[
\frac{d}{dt} \begin{pmatrix}
\rho_{11} & \tilde{\rho}_{12} & \rho_{13} \\
\tilde{\rho}_{21} & \rho_{22} & \tilde{\rho}_{23} \\
\tilde{\rho}_{31} & \tilde{\rho}_{32} & \rho_{33}
\end{pmatrix}
= \frac{i}{\hbar} \begin{pmatrix}
\begin{pmatrix}
\rho_{11} & \tilde{\rho}_{12} & \rho_{13} \\
\tilde{\rho}_{21} & \rho_{22} & \tilde{\rho}_{23} \\
\tilde{\rho}_{31} & \tilde{\rho}_{32} & \rho_{33}
\end{pmatrix},
-\delta_{13} & 0 \\
0 & -(\hbar \omega + \Delta_{3,2}) & \Omega_{1} \exp(-i\omega t) \\
\Omega_{3,1} & \Omega_{1} \exp(-i\omega t) & 0
\end{pmatrix}
\]

\[
-\left( \begin{array}{ccc}
-\rho_{22} & -\rho_{12} & -\rho_{13} \\
\rho_{21} & \rho_{22} \tau_{2}^{-1} & \rho_{23} \tau_{3}^{-1} \\
\rho_{31} & \rho_{32} \tau_{3}^{-1} & \rho_{33} \tau_{3}^{-1}
\end{array} \right).
\]

(2.50)

In general the coupling strength \(\Omega_{1,3}\) is complex, here for simplicity we assume \(\Omega_{1,3} = \Omega_{3,1} = \Omega_{c}\). The off-diagonal density matrix elements are also complex and satisfy \(\bar{\rho}_{ij} = \bar{\rho}_{ji}^*\), where \(i, j \in [1,2,3]\) and \(i \neq j\). Therefore, the independent variables in Eqn. (2.50) can be chosen as the following 9 variables in total:

\(\rho_{11}, \text{Re}(\bar{\rho}_{12}), \text{Im}(\bar{\rho}_{12}), \text{Re}(\rho_{13}), \text{Re}(\bar{\rho}_{23}), \text{Im}(\bar{\rho}_{23}), \text{and} \rho_{33}\), where \(\text{Re}(x)\) and \(\text{Im}(x)\) represent the real and the imaginary parts of \(x\), respectively.

In order to find the steady state solutions for the 9 independent density matrix variables, we can set the left side of Eqn. (2.50) to be 0 and solve it in combination with Eqn. (2.48). In the steady state condition Eqn. (2.50) and Eqn. (2.48) can be expanded to form a set of 9 independent linear equations which are shown below:

\[
\begin{bmatrix}
0 & 0 & 0 & -\Omega_{c} & h\tau_{2}^{-1} & 0 & 0 & 0 & 0 \\
0 & h\tau_{1,2}^{-1} & 0 & -\Omega_{t} & 0 & 0 & \Omega_{c} & 0 & 0 \\
0 & (\Delta_{2,3} - \delta_{1,3}) & h\tau_{1,2}^{-1} & 0 & 0 & \Omega_{c} & 0 & 0 & 0 \\
0 & 0 & h\tau_{1,3}^{-1} & -\Omega_{t} & 0 & 0 & \Omega_{c} & 0 & 0 \\
\Omega_{c} & 0 & 0 & 0 & h\tau_{1,3}^{-1} & 0 & 0 & -\Omega_{c} & 0 \\
0 & 0 & 0 & 0 & 0 & h\tau_{2,3}^{-1} & 0 & 2\Omega_{t} & -\hbar\tau_{3}^{-1} \\
0 & \Omega_{c} & 0 & 0 & 0 & 0 & \Omega_{t} & \Delta_{2,3} & -\hbar\tau_{2,3}^{-1} \\
0 & 0 & \Omega_{c} & 0 & 0 & 0 & 0 & \Delta_{2,3} & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{pmatrix}
\rho_{11} \\
\text{Re}(\bar{\rho}_{12}) \\
\text{Im}(\bar{\rho}_{12}) \\
\text{Re}(\rho_{13}) \\
\text{Im}(\rho_{13}) \\
\rho_{22} \\
\text{Re}(\bar{\rho}_{23}) \\
\text{Im}(\rho_{23}) \\
\rho_{33}
\end{pmatrix}
= \begin{pmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{pmatrix}.
\]

(2.51)
One of the most interesting parameters that can be extracted from Eqn. (2.51) for the steady state density matrix elements is the optical gain \( g(\omega) \), given by the expression [23]

\[
g(\omega) = \frac{\tilde{N}_s e^2 n_{\text{eff}} |z_{32}|^2 \omega}{2d\varepsilon_0\varepsilon_r c \Omega_t} \operatorname{Im}(\tilde{\rho}_{23}) , \tag{2.52}
\]

where \( \tilde{N}_s \) is the sheet doping density per period of active region/injector pair whose thickness is \( d \), \( n_{\text{eff}} \) is the effective modal refractive index of the waveguide, \( \varepsilon_0\varepsilon_r \) is the permittivity of the material, and \( c \) is the speed of light in vacuum. From Eqn. (2.51)-(2.52), the optical gain is solved to be

\[
g(\omega) = \frac{2\tilde{N}_s e^2 n_{\text{eff}} |z_{32}|^2 \omega}{d\varepsilon_0\varepsilon_r c} \times \frac{\Omega_c^2 t_{12,3} (\tau_3-\tau_2)/\hbar^2}{1+\delta_3^2 t_{1,2,3}/\hbar^2 + 2\Omega_c^2 t_{1,2,3} (2\tau_3+\tau_2)/\hbar^2} \times \frac{1+\delta_2^2 t_{1,2,3}/\hbar^2 + \Omega_c^2 t_{1,2,3} (2\tau_3+\tau_2)/\hbar^2}{1+\delta_3^2 t_{1,2,3}/\hbar^2 + \Omega_c^2 t_{1,2,3} (2\tau_3+\tau_2)/\hbar^2} . \tag{2.53}
\]

We can further set the detuning terms \( \Delta_{2,3} \) and \( \delta_{1,3} \) to be 0 and obtain the peak optical gain as a function of the coupling strength \( \Omega_c \)

\[
g_{\text{max}} = \tilde{\xi} \times \frac{\Omega_c^2 t_{1,2,3} (\tau_3-\tau_2)/\hbar^2}{1+\Omega_c^2 t_{1,2,3} (2\tau_3+\tau_2)/\hbar^2} \times \frac{1}{1+\Omega_c^2 t_{1,2,3} (2\tau_3+\tau_2)/\hbar^2} , \tag{2.54}
\]

where

\[
\tilde{\xi} = \frac{4\tilde{N}_s e^2 n_{\text{eff}} |z_{32}|^2 E_{32}}{hd\varepsilon_0\varepsilon_r c} , \tag{2.55}
\]

and \( E_{32} \) is the laser transition energy. Figure 2.7 plots the \( g_{\text{max}}/\tilde{\xi} \) as a function of the coupling strength \( \Omega_c \), assuming \( \tau_3 = 2 \) ps, \( \tau_2 = 0.2 \) ps, and \( \tau_{1,2,3} = 66 \) fs, \( \tau_{1,2,3} = 20 \) fs, \( \tau_{1,2,3} = 13 \) fs (corresponding to transition broadening of 20 meV, 66 meV and 100 meV, similar to those in [20]).

As we can see from Fig. 2.7, the peak optical gain increases monotonously with \( \Omega_c \) at the beginning, and then saturates and roll-over at \( \Omega_c \sim 10 \) meV. For the typical value of \( \Omega_c \sim 3 \) meV employed in most convention QC laser designs, the peak optical gain is actually much lower than the maximum that is achievable. Therefore, in order to effectively suppress the interface roughness induced dephasing to the resonant tunneling process and optimize the optical gain, a much larger coupling strength \( \Omega_c \) between the injector ground state and the upper laser state needs to be employed in the band-structure design. To distinguish it from the conventional strong coupling regime, we refer to this new design strategy as the ultra-strong coupling regime.
Fig. 2.7 The trend of the peak optical gain as a function of the coupling strength $\Omega_c$.

2.5 High performance QC lasers employing ultra-strong coupling design strategy

Following the theoretical analysis of the optimal coupling strength between the injector ground state and the upper laser state, we incorporate the proposed ultra-strong coupling design strategy in real QC laser designs operating in the 4 $\mu$m to 5 $\mu$m range. In this section, we present one of the best performing designs with which a record WPE of QC lasers is achieved.

2.5.1 Band-structure design

In order to increase the coupling strength between the injector ground state and the downstream upper laser state, the spatial overlap between the decaying tails of the two wavefunctions needs to be enhanced, which can be perceived from Eqn. (2.33). A straightforward and effective way to achieve this goal is to decrease the thickness of the thick injection barrier between the two states. We employ such an approach in our ultra-strong coupling QC laser band-structure designs: by reducing the thickness of the injection barrier from a typical value of $\sim$4 nm down to $\sim$1 nm, the coupling strength can be significantly increased to $\sim$10 meV, the estimated optimal range in the ultrastrong coupling regime. The band-structure for one of the best performing designs (wafer No. A785) is shown in Fig. 2.8 [27].
Fig. 2.8 Band-structure of one of the best performing ultra-strong coupling QC laser designs (wafer No. A785). Starting from the widest quantum well, the layer sequence of one period of the active region/injector pair in the electron downstream direction with individual thickness in nanometer is: 4.2/1.2/3.9/1.4/3.3/2.3/2.8/2.6/2.2/2.1/1.8/1.5/1.3/1.2/1.0, where the InAlAs barrier layers are in bold, the InGaAs well layers are in roman. The underlined layers are doped with a bulk doping density of 2.3×10^{17} cm^{-3}, corresponding to a sheet doping density of 1×10^{11} cm^{-2} per period.

Fig. 2.9 Band-structure of the same design in Fig. 2.8 with the localized wavefunctions in the divided bases plotted. One period of active region/injector pair is divided into 3 bases at the barriers indicated by the red dashed lines.
The above QC laser design employs an estimated optimal coupling strength $\Omega_c$ of $\sim 10$ meV (the energy splitting between the two anti-crossed red states in Fig. 2.8 is $\sim 19$ meV, corresponding to $2\Omega_c$), which is much stronger compared to those in conventional designs ($\sim 2$–4 meV). This is achieved by adopting a much thinner injection barrier ($\sim 1$ nm vs. $\sim 3$–4 nm in most conventional designs) between the injector and the active region. In addition, such a design approach has other benefits for the electron transport: the stronger coupling (thinner barrier) leads to stronger anti-crossing and a reduced Stark shift (i.e., the energy detuning due to the change in the applied electric field) between the injector ground state and the downstream upper laser state, which consequently make the alignment of the two energy levels more stable when subjected to a change in the external bias; and furthermore, the resonant tunneling rate also becomes less susceptible to the detuning between the two states according to Eqn. (2.42).

The wavefunctions plotted in Fig. 2.8 are the eigenstates of the entire periodic structure, therefore it can be difficult to extract the exact coupling strength between the injector ground state and the downstream upper laser state in such a picture due to the coupling with the other states. On the other hand, the whole structure can be divided at certain relatively thick barriers to form bases as shown in Fig. 2.9, and all the states including the injector ground state and the upper laser state are treated as eignestates associated with the bases in which they are localized. In such a picture, the coupling strength between two states from different bases can be readily calculated with a tight-binding approach. With the choice of bases shown in Fig. 2.9, the coupling strength between the injector ground state (green) and the downstream upper laser state (red) is calculated to be $\sim 8.5$ meV. However, it is worth noting that for this band-structure design the choice of bases are not absolutely decisive since no exceedingly thick barrier is present. The coupling strength calculation is critically dependent on the choice of bases and therefore contains a certain degree of ambiguity, nevertheless, it is clear that the coupling strength is significantly enhanced in this design in comparison with conventional designs.
Besides that the ultra-strong coupling is expected to effectively overcome the interfacenoughness-induced dephasing of the resonant tunneling process and lead to a more optimal tunneling current, another concurrent advantage of such an ultra-strong coupling design is that the upper laser state spreads more into the injector region as a result of the thin injection barrier, so that the radiative transition is more diagonal rather than vertical, which increases the upper laser level lifetime and consequently improves the slope efficiency (see Eqn. (2.26)) and decreases the threshold current density thanks to a larger population inversion.

The entire band-structure design makes use of strain balanced InGaAs/AlInAs material system to provide large enough band-offset for the relatively short wavelength operation. The designed materials compositions are In$_{0.66}$Ga$_{0.34}$As/Al$_{0.69}$In$_{0.31}$As, and the corresponding band-offset is ~890 meV. The active region design is based on three quantum wells, the radiative transition energy is designed to be ~260 meV, and two resonant LO-phonons depopulation scheme [28] is adopted to efficiently depopulate the lower laser state (the blue state in Fig. 2.8). The injector consists of 5 quantum wells, within which a narrow and relatively flat miniband of several strongly coupled states are formed to facilitate the electron transport via a combination of different scattering mechanisms and resonant tunneling. The total energy defect for suppressing the thermal back-filling at high temperature is designed to be ~80 meV.

2.5.2 Waveguide structure design

The active core of this QC laser design contains 43 periods of active region/injector pairs with a total thickness of ~1.5 µm. In order to achieve a large mode confinement factor and a low waveguide loss, the following waveguide structure design is employed: from the substrate up, the layers sequence is (1) a 2 µm thick InP bottom waveguide cladding layer with low doping density of $2.0 \times 10^{16}$ cm$^{-3}$; (2) the 1.5 µm thick active core with average doping density of $2.9 \times 10^{16}$ cm$^{-3}$; (3) a 2.3 µm thick InP top waveguide cladding layer with low doping density of $2 \times 10^{16}$ cm$^{-3}$; (4)
an additional 0.8 µm thick InP top waveguide cladding layer with doping density of $5 \times 10^{18} \text{ cm}^{-3}$; (5) a 0.2 µm thick highly doped InP top contact layer with doping density of $2 \times 10^{19} \text{ cm}^{-3}$; (6) another 0.2 µm thick highly doped InGaAs top contact layer with doping density of $2 \times 10^{19} \text{ cm}^{-3}$.

The one-dimensional (in the direction perpendicular to the material layers) transverse mode profile of the waveguide structure is simulated and plotted in Fig. 2.10. Several key waveguide parameters influencing the laser performance are extracted, e.g., the effective modal refractive index is calculated to be ~3.255, and the mode confinement factor $\Gamma$ is estimated to be ~0.76.

![Waveguide structure design for wafer A785 and the transverse mode profile.](image)

Fig. 2.10 Waveguide structure design for wafer A785 and the transverse mode profile.
2.5.3 Device fabrication

The QC laser structure is grown by MOCVD on low doped InP substrate by our collaborators at AdTech Optics. The n-type dopant incorporated in the epitaxial layers is silicon atoms. Figure 2.11 shows the doping profile in the epitaxial growth direction characterized with secondary ion mass spectroscopy (SIMS). The measured doping levels are relatively close to the designed values.

Ridge waveguide QC lasers are fabricated with ridge widths varying from 13.5–21.5 µm using conventional III-V semiconductor processing techniques. The ridges are patterned with photolithography and then wet-etched to ~8 µm deep; ~0.3 µm SiOₓ insulation layer is deposited with plasma enhanced chemical vapor deposition (PECVD); contact windows are opened at the top of the ridges with photolithography and reactive-ion etching (RIE); contact patterns are again defined with photolithography and thin 30/300 nm Ti/Au top metal contact is deposited through electron-beam evaporation from three different angles to ensure high-quality coverage on the ridge sidewalls and corners; the substrate is then thinned down to ~ 200 µm and 20/200 nm Ge/Au bottom metal contact is deposited through electron-beam evaporation. Circular mesa samples with diameter of ~190 µm for electroluminescence (EL) and electron transport measurements are also fabricated from the same wafer with similar techniques except that no SiOₓ insulation layer is applied. Ridge QC lasers with cavity lengths varying from ~0.5–4.0 mm and as-cleaved facets are mounted epitaxial-side up to copper heat-sinks. QC Lasers with buried-heterostructure waveguide and fixed cavity length of ~1.9 mm are also fabricated, with the back-facets coated with layers of SiO₂/Ti/Au (150 nm/20 nm/150 nm, deposited through electron-beam evaporation) for high-reflectivity (HR), and mounted epitaxial-side up to copper heat-sinks. Exemplary images of fabricated devices are shown Fig. 2.12, taken with both optical microscope and scanning electron microscope (SEM).
Fig. 2.11 Profiles of the material composition elements, the silicon dopant and other impurity atoms in the epitaxial layers characterized with SIMS.

Fig. 2.12 (a) Optical microscope image of a packaged ridge waveguide QC laser chip. (b) SEM image of a QC laser as-cleaved facet.
2.5.4 Device characterization results

A large number of fabricated QC lasers with various ridge widths and lengths are fully characterized, including their lasing spectra and LIV characteristics across a wide range of temperatures. Several mesa samples cleaved into halves are also characterized for the EL spectra and IV characteristics. The spectra are measured with a Fourier transform infrared spectrometer (FTIR). The details of the experimental setups for the spectra and LIV characterizations are described in Appendix A.

Figure 2.13 shows the EL spectra of a mesa sample measured at 80 K and 300 K, respectively. The peak positions of the spectra are close to the designed transition energy. In addition, the EL spectra appear not to be significantly broadened by the ultra-strong coupling between the injector ground state and the downstream upper laser state, that their FWHM values are comparable to (slightly larger than) those of the conventional designs at similar wavelength range.

Fig. 2.13 Spectra of the EL of a mesa sample at 80 K and 300 K, respectively.
IV characteristics of the non-lasing mesa samples (Fig. 2.14) suggest significantly improved electron transport properties. This can be seen more clearly when compared to an exemplary high performance conventional design of similar wavelength and sheet doping density: the IV characteristics of the ultra-strong coupling mesa sample show both higher maximum operating current densities and lower differential resistance across a large temperature range (Fig. 2.15). Moreover, the dynamic voltage range, i.e., the difference between the turn-on voltage and the voltage at the maximum operating current density, is ~45% and ~75% of the turn-on voltage in the ultra-strong coupling design at 80 K and 300 K, respectively, compared to ~28% and ~60% in the conventional design. The difference in the turn on voltage is mainly due to the different number of stages in the two designs.

The spectra of the QC lasers are characterized at various heat-sink temperatures mostly in pulsed mode operation. Representative laser spectra measured slightly above the threshold current are shown in Fig. 2.16; the lasing wavelength is ~4.5 µm at 80 K and ~4.7 µm at room temperature, close to the designed operating wavelength.
Fig. 2.15 Comparisons of electron transport properties (IV characteristics) of the ultra-strong coupling design and an exemplary conventional design of similar wavelength (~4.7 µm at 80 K) at 80 K (a) and at 300 K (b).

Fig. 2.16 Representative laser spectra at 80 K and 300 K.
Fig. 2.17 (a) Pulsed LIV measurements for an as-cleaved 13.6 µm wide, 2.9 mm long QC laser at various heat sink temperatures as indicated. The measured single-facet optical power is doubled for two facets (a process we have tested to be valid for as-cleaved Fabry-Perot QC lasers) and corrected for the optical collection efficiency of the experimental setup (0.74, calculated from the far-field measurement of the laser in Fig. 2.18). (b) The WPE versus current is extracted from the measurement results in (a) (not corrected for the wiring resistance).

LIV characterization results of these QC lasers show significant improvements in the device overall performance, especially in the slope efficiency, peak power level and WPE, across a broad range of temperatures compared to those of the best previously reported QC lasers at similar wavelengths and operating conditions [4,9]. Figure 2.17 shows the LIV characteristics and the calculated WPE for one of the best performing QC lasers (a 13.6 µm wide and 2.9 mm long ridge with as-cleaved facets) in pulsed mode operation (5 kHz repetition rate, 100 ns pulse width) at various heat-sink temperatures. It exhibits a high slope efficiency of ~8 W/A, at least ~10.0 W peak optical output power, and a maximum WPE of ~47% at 80 K. The WPE further increases to more than 48% when operated at 9 K. If taking into account the ~0.35 Ω measured wiring resistance from the pulse generator to the device, the WPE essentially reaches 50% at 9 K. This is a record breaking WPE at the time this work was reported and a major step forward from the previously reported best result (~34%) [4,9]. Even at higher temperature above 200 K, the high slope efficiency is still well maintained and the peak WPE is ~35% at 200 K. In order to accurately measure the output optical
power, the laser beam far-field profiles (Fig. 2.18) are characterized and the optical collection efficiency of the measurement setup is calculated.

![Far-field measurements of the laser beam profiles along the growth direction and the in-plane direction. The beam divergence angles at FWHM are ~41° along the growth direction and ~28° along the in-plane direction, respectively. The symbols are the measured data points, and the lines are the corresponding fitting curves.](image)

The high performance QC laser reported above is not an exceptional device. In fact, most of the characterized devices with similar cavity length exhibit similar high performance. Figure 2.19 shows a scatter plot of the pulsed-mode peak WPE at 80 K for all tested lasers with cavity lengths varying from 2.3–3.0 mm. The majority of the tested devices in this cavity length range have a peak WPE greater than 40% at 80 K, several of them have a peak WPE greater than 45% (the data points in the plot have not been corrected for the wiring resistance). Waveguide loss of ~1.5 cm\(^{-1}\) is extracted from standard “1/L” measurements (Fig. 2.20), and such a relatively low waveguide loss value is also beneficial for achieving such high laser WPE. Two advantageous features of this design, i.e., the greatly improved maximum operating current density and the high slope efficiency, are maintained at high temperatures. The slope efficiency drops < 5% from 9 K to 160 K, and in the temperature range from 160 K to 300 K a very high characteristic temperature of the slope efficiency \(T_1\) of ~330 K is
extracted, whereas for conventional QC lasers $T_1$ is usually below 300 K in the same temperature range. A characteristic temperature $T_0$ of ~125 K is extracted from the threshold current density versus temperature plot in Fig. 2.21. This relatively low $T_0$ is suspected to be largely due to the relatively low two-LO-phonon energy defect employed for this particular design which favors low temperature operation but limits the laser threshold performance and hence the WPE at high temperature due to significant thermal back-filling effect.

Fig. 2.19 Scatter plot of pulsed-mode peak WPE at 80 K for all tested QC lasers with various cavity lengths.
Fig. 2.20 Waveguide loss measurement at 80 K with “1/L” method. Waveguide loss of 1.5 cm\(^{-1}\) and modal gain coefficient of 13.9 cm/kA are extracted.

Fig. 2.21 Extraction of the characteristic temperature \(T_0\) from the threshold current density vs. operating temperature plot. \(T_0\) is found to be \(\sim125\) K.
These QC lasers have also been characterized in CW mode operation at cryogenic temperatures. The same laser shown in Fig. 2.17 has a peak CW power of at least 6.0 W and 4.5 W at 30 K and 80 K, respectively (Fig. 2.22(a)). Maximum values of the CW WPE of 32% at 30 K and 28% at 80 K are extracted (Fig. 2.22(b)). They are significantly lower, however, than the pulsed results at the same temperatures. This is largely due to the rapid heating-up of the laser active core as the device fabrication and packaging techniques employed are not aimed at optimizing the CW operation.

Fig. 2.22 (a) CW LIV characteristics for the same laser shown in Fig. 2.17 at heat-sink temperatures of 30 K and 80 K. The measured single-facet optical power is doubled for two facets and corrected for the optical collection efficiency of 74%. (b) The CW WPE versus current extracted from the results in (a).

QC lasers with a buried-heterostructure waveguide are also fabricated. However, these devices have limited cavity length (maximum 1.9 mm) and thus HR coating is necessary for achieving high performance. Figure 2.23 shows the pulsed LIV characteristics of a back-facet HR-coated buried-heterostructure QC laser and the calculated WPE only taking into account the optical power from the front facet. It has similar high slope efficiency (~8W/A) and high output optical power level, and reaches ~44% WPE at 80 K and ~16% at 300 K. Figure 2.24 shows its CW LIV characteristics, which exhibits an improved CW performance in terms of usable optical power level,
maximum operating temperature (230 K) compared to the simple ridge QC lasers. The CW performance is expected to be further improved with more advanced fabrication processes (e.g. thick electro-plated gold for top contact) and/or packaging techniques (e.g. epitaxial-side down mounting, diamond heat-sink) for faster heat removal.

Fig. 2.23 (a) Pulsed LIV characteristics for a buried-heterostructure QC laser (14 µm wide and 1.9 mm long) with back-facet HR coating at various heat-sink temperatures. Optical power is only measured from the front-facet, and is corrected for optical collection efficiency of 74%. (b) The pulsed WPE versus current extracted from the experimental results in (a).

Fig. 2.24 (a) CW LIV characteristics for the same laser in Fig. 2.23 at various heat-sink temperatures. Optical power is only measured from the front-facet, and is corrected for optical collection efficiency of 74%. (b) The CW WPE versus current extracted from the experimental results in (a).
To summarize this section, we have experimentally realized a new QC laser design employing ultra-strong coupling between the injector ground state and the downstream upper laser state. The significantly increased coupling strength effectively overcomes the interface-roughness-induced dephasing of the resonant tunneling process and facilitates the electron transport, which in turn greatly improves the QC laser performance, such as the slope efficiency, the output optical power and especially the WPE. An unprecedented ~50% WPE is experimentally demonstrated.

2.6 Ultra-strong coupling QC lasers with broad-band optical gain

In addition to improving the power performance of QC lasers, the ultra-strong coupling design strategy can also be exploited to achieve broad-band optical gain, which is highly interesting for applications such as multi-species molecular sensing, spectrometer sources and frequency combs in mid-IR wavelength range. Three features associated with the ultra-strong coupling regime offer the potential for realizing broad optical gain spectrum. First of all, according to Eqn. (2.43) the broadening of the radiative transition between the upper laser state and the lower laser state tends to be larger for ultra-strong coupling designs because the upper laser state partially extends into the injector region and experience more interfaces that are not seen by the lower laser state. Secondly, the injector ground state is strongly coupled with the downstream upper laser state and therefore also has significant contribution to the radiative transition. The broadening of the transition between the injector ground state and the lower laser state is expected to be large because of their small spatial overlap. Last but not least, the larger coupling strength introduces a larger energy splitting between the two anti-crossed states which directly adds to the optical gain spectrum width. In fact, the three factors are all reflected in Eqn. (2.53) for the optical gain calculation based on the density matrix model. Moreover, more than two states can be strongly coupled to further broaden the optical gain spectrum [29,30]. In this section, a QC laser design employing both ultra-strong coupling and short injector design strategies is presented, with which an exceedingly broad-band optical gain is realized.
2.6.1 Band-structure design

Figure 2.25 shows the band-structure design with the wavefunctions of the eigenstates associated with the entire periodic structure plotted. The entire band-structure design makes use of strain balanced InGaAs/AlInAs material system to provide large enough band-offset for the relatively short wavelength operation. The designed materials compositions are In$_{0.62}$Ga$_{0.38}$As/Al$_{0.70}$In$_{0.30}$As, and the corresponding band-offset is ~870 meV. The three states in red extending through an entire period are strongly coupled with each other and all contribute to the optical gain. The lower laser state is plotted in blue. The radiative transition energy is designed to be ~210 meV, corresponding to an emission wavelength of ~6 μm. The active region makes use of two resonant LO-phonons depopulation scheme, and the total energy defect is designed to be ~85 meV.

The origin of the 3 strongly coupled upper laser states can be seen more clearly from Fig. 2.26, which plots the wavefunctions of the eigenstates associated with the bases. Here, one stage of the QC structure is divided in two bases: the active region and the short injector, and the boundaries between them are shown in the red dashed lines. The injector ground state (plotted in green) couples to both the excited state in the downstream active region (plotted in red) and the lowest ground state in the upstream active region (plotted in purple), with calculated coupling strength of 10.9 meV and 9.5 meV, respectively, belonging to the ultra-strong coupling regime. Due to the compactness of the injector, the 3 states couple to each other simultaneously and form the 3 extended upper laser states. The width of the optical gain for such a design is expected to be much larger than that for a conventional design with the upper laser state localized in the active region.
Fig. 2.25 Band-structure of the broad-band optical gain ultra-strong coupling QC laser design (wafer No. A1392). Starting from the widest quantum well, the layer sequence of one period of the active region/injector pair in the electron downstream direction with individual thickness in nanometer is: 5.45/1.0/4.5/1.3/3.4/1.75/2.8/1.55/2.1/1.5, where the InAlAs barrier layers are in bold, the InGaAs well layers are in roman. The underlined layers are doped with a bulk doping density of $2.2 \times 10^{17}$ cm$^{-3}$, corresponding to a sheet doping density of $\sim 1 \times 10^{11}$ cm$^{-2}$ per period.

Fig. 2.26 Band-structure of the same design in Fig. 2.25 with the localized wavefunctions in the divided bases plotted. One period of active region/injector pair is divided into 2 bases at the barriers indicated by the red dashed lines.
2.6.2 Waveguide design

The active core of this QC laser design contains 50 periods of active region/injector pairs with a total thickness of ~1.3 µm. The waveguide structure is designed to have the following structure: from the substrate up, the layers sequence is (1) a 2 µm thick InP bottom waveguide cladding layer with low doping density of $2.0 \times 10^{16} \text{ cm}^{-3}$; (2) the 1.3 µm thick active core with average doping density of $3.8 \times 10^{16} \text{ cm}^{-3}$; (3) a 2.5 µm thick InP top waveguide cladding layer with low doping density of $2 \times 10^{16} \text{ cm}^{-3}$; (4) an additional 0.8 µm thick InP top waveguide cladding layer with doping density of $5 \times 10^{18} \text{ cm}^{-3}$; (5) a 0.1 µm thick highly doped InP top contact layer with doping density of $2 \times 10^{19} \text{ cm}^{-3}$; (6) another 0.1 µm thick highly doped InGaAs top contact layer with doping density of $2 \times 10^{19} \text{ cm}^{-3}$. The one-dimensional (in the direction perpendicular to the material layers) transverse mode profile of the waveguide structure is simulated and plotted in Fig. 2.27. Several key waveguide parameters influencing the laser performance are extracted, e.g., the effective modal refractive index is calculated to be ~3.195, and the mode confinement factor $\Gamma$ is estimated to be ~0.54. It should also be noticed in Fig. 2.27 that the transverse mode is weakly coupled into the surface plasmon mode in the highly doped top contact layer, and therefore would incur higher waveguide loss.

2.6.3 Device characterization results

The QC laser structure is grown by MOCVD on low doped InP substrate by our collaborators at AdTech Optics. Ridge waveguide QC lasers with various ridge widths and lengths and circular mesa samples for EL and electron transport measurements are fabricated and packaged using the same processes described in the previous section. The devices are then fully characterized for their spectral and LIV (IV for non-lasing mesa samples) characteristics.
The EL from non-lasing half-circular mesa samples is characterized and indeed exhibit very broad spectra across the entire operating temperature range from 80 K to 300 K. Figure 2.28(a) shows the EL spectra measured at current density of 1 kA/cm$^2$ and at 80 K, 200 K, and 300 K, respectively. The FWHM of the EL spectra at various temperatures are plotted in Fig. 2.28(b), together with the information of the percentage of the transition energy the spectra width corresponds to. At 80 K, the FWHW of the EL spectra corresponds to $\sim$30% of the transition energy, and it increases almost linearly to $\sim$40% at 300 K. Such values are much larger than what is usually achieved with conventional QC laser designs, and are comparable to the state-of-the-art broad-band optical gain QC laser designs ($\sim$40%) [31].
Fig. 2.28 (a) EL spectra measured from a half-circular mesa operated at 1 kA/cm² current density and various temperatures. (b) FWHM of the EL spectra at various operating temperatures and the percentage of the transition energy they correspond to.

Fig. 2.29 IV characteristics for a circular non-lasing mesa at various operating temperatures.

The IV characteristics of non-lasing mesa samples are characterized (Fig. 2.29) and show similar features as those of the ultra-strong coupling design (A785) described in Section 2.6, including low differential resistance, large operating current density and voltage range (up to current density of more than 10 kA/cm², no obvious kink or increase of differential resistance is observed in the IV curves), which indicate good electron transport property.
Representative laser spectra at 80 K and 300 K are shown in Fig. 2.30. The emission wavelength at 80 K is slightly longer than the designed value, and it is abnormally red-shifted in comparison with the emission wavelength at 300 K (for most QC laser designs the emission wavelength red-shifts with increasing temperature). The discrepancy of the emission wavelength from its designed value and the unusual temperature dependence of the emission wavelength may be attributed to the relatively early turn-on of the current flow as a result of the ultra-strong coupling and the short injector employed.

Figure 2.31 shows the LIV characteristics of a representative laser and the calculated WPE in pulsed mode operation across a large temperature range. From the threshold voltage, the electric field applied across the device structure is ~100 kV/cm, much lower than the designed electric field (~125 kV/cm) for the three strongly coupled states to be in full resonance. Compared to the high performance QC lasers in the previous section, the threshold current density at 80 K for these QC lasers operating at ~6.3 µm is higher and also increases faster with temperature, corresponding to a low characteristic temperature of ~107 K (Fig. 2.32). The higher threshold current density can be attributed to both a lower waveguide mode confinement factor ($\Gamma \approx 0.54$) which limits the modal gain and a higher waveguide loss of ~5.3 cm$^{-1}$ (Fig. 2.33).
Fig. 2.31 (a) Pulsed LIV characteristics for a representative QC laser (3 mm long and 16.3 µm wide ridge) at various heat-sink temperatures. (b) WPE calculated from the experimental results in (a).

Fig. 2.32 Characteristic temperature $T_0$ ($\approx 107$ K) extracted from the threshold current versus operating temperature plot.
Fig. 2.33 Waveguide loss at 80 K extracted with the “1/L” method.

The waveguide loss is extracted with standard “1/L” method at 80 K and is found to be \( \sim 5.3 \text{ cm}^{-1} \), much higher than that of the high performance wafer A785, which in turn can be attributed to the longer emission wavelength (free carrier absorption is proportional to the emission wavelength squared) and the weak coupling of the transverse mode to the surface plasmon mode in the highly doped top contact layer as can been see in Fig. 2.27. This relatively large waveguide loss is a significant limiting factor for the QC laser performance, including the threshold current density, the slope efficiency, the optical power level as well as the maximum WPE that can be achieved. The overall performance for this QC laser design is expected to be further improved with a more optimized waveguide design.

The characteristic temperature \( T_0 \) for both the high performance ultra-strong coupling design in the previous section and the broad-band optical gain design employing ultra-strong coupling and short injector reported above are relatively low compared to state-of-the-art conventional QC lasers, and considerably limit the device performance at high temperatures (e.g. room temperature) and in CW mode, which are highly desired for many real-world applications. In both designs, the energy defects employed between the lower laser state and the injector ground state are relatively low compared to those of the best performing conventional QC laser designs, leading to more severe
thermal backfilling when operated at high temperatures. This may well be a contributing factor for the relatively low $T_0$. In addition, for the broad-band optical gain design, the laser slope efficiency also deteriorates relatively fast with increasing temperature, indicating other mechanisms such as significant carrier leakage may also play a role in limiting the device performance at high temperatures. How to further improve the device performance at high temperature is a key question.

In the next section, systematic and comparative study on the performance of a number of different ultra-strong coupling QC lasers are presented, with an emphasis on factors influencing the temperature performance.

### 2.7 Influence of taller electron exit barriers on the temperature performance of ultra-strong coupling QC lasers

Besides the two reported in the previous two sections, we have implemented the ultra-strong coupling design strategy in a number of other QC laser designs (12 designs in total, see Appendix B) mostly in the wavelength range of 4 $\mu$m to 5 $\mu$m. They are designed for different purposes and have differences in various aspects of the band-structure. Some of them perform better than the others. By comparing the device performance and certain device parameters across some or all the designs, we can gain insight on which parameters have higher impact on the device performance and how to adjust them to further improve the device performance.

One of the most important goals for our design exploration is to identify the major causes for the relatively low characteristic temperatures observed in several ultra-strong coupling designs and find out effective ways to improve the characteristic temperatures. If the waveguide loss does not change with temperature significantly, then a relatively low characteristic temperature is a result of relatively fast degrading of the population inversion with increasing temperature. There are two major causes for such temperature dependent population inversion degradations: thermal backfilling of electrons from the injector ground state to the lower laser state and electron leakage from the upper laser state due to thermal excitation. In order to investigate the influence of these two factors on the
temperature performance of ultra-strong coupling QC lasers, we design two pairs of ultra-strong coupling QC lasers with contrasting features. The first pair of designs employs the two resonant LO-phonons depopulation scheme while the second pair employs the three resonant LO-phonons depopulation scheme, and therefore the energy defect is different for the two pair of designs. By comparing the temperature performance between the two pairs of designs, we expect to see whether the thermal backfilling is a significant factor limiting the laser characteristic temperature. Within each pair, the two designs are almost identical except for the two barriers after the active region which we refer to as the electron exit barriers. The difference is that the electron exit barriers in one design are made taller by changing the material composition, and such taller barriers have been demonstrated to be capable of suppressing the electron leakage into the continuum states above the barriers [32,33], therefore comparisons between the baseline design and the taller-barrier design would provide us with information on the influence of the electron leakage into the continuum on the characteristic temperature.

Fig. 2.34 Band-structures for the pair of two-LO-phonon designs. The top one is the base line design (wafer No. A1641) while the bottom one is the taller-barrier design (wafer No. A1643).
2.7.1 Band-structure designs

The pair of two-LO-phonon designs are shown in Fig. 2.34 and the pair of three-LO-phonon designs are shown in Fig. 2.35. The baseline two-LO-phonon design has a radiative transition energy of ~255 meV and an energy defect of ~82 meV. The coupling strength between the injector ground state and the downstream upper laser states is ~17 meV. Starting from the widest quantum well, the layer sequence of one period of the active region/injector pair in the electron downstream direction with individual thickness in nanometer is:

4.2/1.2/3.9/1.4/3.3/2.25/3.05/2.2/2.4/2.0/1.8/1.8/1.5/1.3/1.2/1.0, where the In$_{0.31}$Al$_{0.69}$As barrier layers are in bold, the In$_{0.66}$Ga$_{0.34}$As well layers are in roman. The underlined layers are doped with a bulk doping density of 2.0×10$^{17}$ cm$^{-3}$, corresponding to a sheet doping density of 8.8×10$^{10}$ cm$^{-2}$ per period. In the taller-barrier two-LO-phonon design, the middle parts of two electron exit barriers are made taller by ~240 meV (In$_{0.11}$Al$_{0.89}$As), while the rest of the design details are identical to the baseline design. The baseline three-LO-phonon design has a radiative transition energy of ~260 meV and an energy defect of ~122 meV. The coupling strength between the injector ground state and the
downstream upper laser states is ~16 meV. Starting from the widest quantum well, the layer sequence of one period of the active region/injector pair in the electron downstream direction with thickness in nanometer is: \(4.15/0.9/3.8/1.1/3.25/1.1/2.9/1.8/2.35/1.45/2.05/1.45/1.75/1.45/1.55/1.45/1.45/1.15\), where the \(\text{In}_{0.21}\text{Al}_{0.79}\text{As}\) barrier layers are in bold, the \(\text{In}_{0.68}\text{Ga}_{0.32}\text{As}\) well layers are in roman. The underlined layers have a bulk doping density of \(1.0 \times 10^{17} \text{ cm}^{-3}\), corresponding to a sheet doping density of \(7.3 \times 10^{10} \text{ cm}^{-2}\) per period. In the taller-barrier three-LO-phonon design, the two electron exit barriers are made taller by ~130 meV (\(\text{In}_{0.12}\text{Al}_{0.88}\text{As}\)), while the rest of the design details are identical to the baseline design.

2.7.2 Device characterization results

The two pairs of QC laser designs are grown by MOCVD on low doped InP substrate by our collaborators at AdTech Optics back-to-back to ensure similar growth quality. QC lasers and circular mesa samples from the four wafers are fabricated with standard processes described previously. The comparisons of the EL spectra within each pair of designs are shown in Fig. 2.36 (two-LO-phonon designs) and Fig. 2.37 (three-LO-phonon designs), respectively.

As shown in Fig. 2.36 and Fig. 2.37, the peak positions of the EL all accurately match the designed radiative transition energies. For the two designs of either pair, the spectra of their EL at the same current density are very similar at both 80 K and 300 K, though the width for the EL spectra of the taller-barrier designs are mostly slightly larger than those for the baseline designs for both pairs. The broader EL spectra associated with the taller-barrier designs can be explained by the stronger interface roughness induced broadening effect to the radiative transitions as a result of the larger band offset at the taller barriers. However, the EL spectrum of the three-LO-phonon taller-barrier design at 80 K (but not at 300 K) is considerably broader than its baseline counterpart, and the underlying cause is unclear.
Fig. 2.36 EL spectra for the two-LO-phonon baseline design (top) and the two-LO-phonon taller-barrier design (bottom) at 80 K and 300 K.

Fig. 2.37 EL spectra for the three-LO-phonon baseline design (top) and the three-LO-phonon taller-barrier design (bottom) at 80 K and 300 K.
Fig. 2.38 Representative QC laser LIV characteristics for the two-LO-phonon baseline design (a) and the taller-barrier design (c), together with the extracted characteristic temperatures (b) and (d).
Fig. 2.39 Representative QC laser LIV characteristics for the three-LO-phonon baseline design (a) and the taller-barrier design (c), together with the extracted characteristic temperatures (b) and (d).

The representative LIV characteristics for QC lasers from 4 different designs are shown in pairs in Fig. 2.38 (two-LO-phonon designs) and Fig. 2.39 (three-LO-phonon designs), together with the extracted values for their characteristic temperature $T_0$. Comparing the LIV characteristics in Fig. 2.38 (a) and (c), we see that the two-LO-phonon baseline design and the taller-barrier design have similar performance in terms of threshold current density and slope efficiency (the maximum output optical power cannot be directly compared due to the difference in ridge widths) at cryogenic temperatures (e.g. 80 K), while at room temperature the taller-barrier design has moderately lower threshold current density and higher slope efficiency, and at 390 K the taller-barrier design has much
better performance. The characteristic temperature of the taller-barrier design is ~30 K higher than that of the baseline design (163 K vs. 133 K). Comparing the LIV characteristics in Fig. 2.39 (a) and (c), we see that the three-LO-phonon taller-barrier design has much better slope efficiency than the baseline design across the entire temperature range. However, the baseline design has a lower threshold current density at 80 K, but its threshold current density increases relatively faster with temperature than that of the taller-barrier design. The characteristic temperature of the taller-barrier design is also ~30 K higher than that of the baseline design (181 K vs. 152 K). Therefore, in both cases the characteristic temperatures are increased by ~30 K with taller electron exit barriers. Such a large difference in the characteristic temperatures suggests that the electron leakage into continuum states through thermal excitation can be significant in these ultra-strong coupling designs, and employing taller electron exit barriers is an effective way of suppressing such an electron leakage path and improve the device high temperature performance.

On the other hand, the characteristic temperatures for the pair of three-LO-phonon designs are higher than those of the pair of two-LO-phonon designs by ~20 K. This observation indicates that the thermal backfilling effect also plays a non-negligible role in limiting the device temperature performance at least for the two-LO-phonon designs. Therefore, for future optimizations of the ultra-strong coupling designs aiming at better high temperature performance, both design strategies investigated above, taller electron exit barriers and larger energy defect, may prove to be effective if properly incorporated.

2.8 Conclusions and discussions

In this chapter we have first derived the WPE expression for QC lasers and analyzed the crucial impact of the electron transport property on the QC laser overall performance. Then we have reviewed several major electron transport processes in QC lasers and studied in depth the resonant tunneling process based on the density matrix formalism. We have found that due to the strong
dephasing in connection with the interface roughness induced intrasubband scattering, the resonant tunneling process between the injector ground state and the downstream upper laser state is likely the bottleneck for the electron transport through the device. Such an interface roughness induced dephasing effect was long underestimated in conventional QC laser design, that the coupling strength employed in most conventional QC laser designs was not sufficient to effectively overcome its negative influence on the resonant tunneling process. Therefore, we have proposed to employ a much larger coupling strength in QC laser band-structure designs which we refer to as the ultra-strong coupling design strategy, and calculated the optimal coupling strength with our density matrix based model. By implementing the ultra-strong coupling design strategy in real QC lasers, we have demonstrated a major step forward in the overall device performance and achieved a record breaking QC laser WPE of \(~50\%\). In addition, this design strategy has been applied to realization of QC lasers with exceedingly broad optical gain. We have further explored different design strategies combined with the ultra-strong coupling to effectively improve the temperature performance of these QC lasers.

It is worth pointing out that the optimal coupling strength is critically dependent on certain material parameters such as the interface roughness average height and correlation length, etc. These material parameters are mostly determined by the epitaxial growth technology employed. Therefore, if the epitaxial growth technologies further improve, the optimal coupling strength would also change accordingly. Of course, the optimal coupling strength also depends on the material systems used, especially on the values of the band offset.

The large number ultra-strong coupling designs we implemented also allow us to cross compare their performance and identify certain key parameters whose influence on the device performance would be difficult to extract from individual designs. For example, we have observed that the energy difference between the upper laser state and the band edge of the lowest satellite valleys (L-valleys for these designs) of the quantum well material (\(\Delta E\), see Fig. 2.40) may have a significant impact on the optical gain coefficient. Such an observation is obtained by comparing the performance of 11 different ultra-strong coupling designs with emission wavelengths in the range of
∼4 µm to 5 µm. (The wafer No. for these 11 designs are A728, A785, E109318, A1015, A1162, A1390, M1065, A1637, A1639, A1641 and A1643. See Appendix B for details of these designs.) Despite the similar operating wavelengths, comparable coupling strengths and almost identical waveguide structures employed, the 11 different designs exhibit a wide range of modal gain coefficients (extracted from standard “1/L” method at 80 K) and FWHM of the optical gain spectra. If assuming the electron injection efficiency is unity, then the gain coefficient at the peak of the optical gain spectrum satisfy the expression [34]

\[ g = \frac{\text{FOM}}{L_p \gamma_{32}}, \]  

(2.56)

where \( L_p \) is the thickness of one period of the active region/injector pair, \( \gamma_{32} \) is the FWHM of the optical gain spectra, and FOM is the figure of merit associated with the design and is defined as

\[ \text{FOM} = \tau_3 (1 - \frac{\tau_2}{\tau_3}) \frac{\Delta m \zeta_3^2}{\epsilon \lambda_0 n_{eff}}, \]  

(2.57)

where most of the parameters are defined previously and \( \lambda_0 \) is the emission wavelength. In fact, the FOM values for all the 11 designs are also similar. According to Eqn. (2.56) the gain coefficient is inversely proportional to the optical gain spectra width and \( L_p \), however, the variation in the gain coefficient of the 11 designs cannot be well explained by the variation in the \( L_p \cdot \gamma_{32} \) as shown in Fig. 2.41(a), that the correlation between the modal gain coefficient and the inverse of \( L_p \cdot \gamma_{32} \) is not satisfactory. Therefore, the gain coefficient cannot be fully accounted for by Eqn. (2.53).

Fig. 2.40 Illustration of the definition of \( \Delta E \), the energy difference between the upper laser states (red) and the band edge of the lowest satellite valleys of the quantum well material (orange dashed line).
Fig. 2.41 (a) Correlation plot for modal gain coefficient versus $1/(L_p \cdot \gamma_{32})$. (b) Correlation plot for modal gain coefficient versus $\Delta E$. (c) Correlation plot for modal gain coefficient versus $\Delta E/(L_p \cdot \gamma_{32})$. 
On the other hand, a clear correlation is found between the modal gain coefficient and $\Delta E$ as shown in Fig. 2.41(b), suggesting that scattering of electrons from the injector ground state and/or the upper laser state into the relatively low-lying satellite valleys associated with the highly strained quantum well material may be significant and effectively reduces the electron injection efficiency. If taking into account all three factors: $L_p$, $\gamma_{32}$ and $\Delta E$, then a much stronger correlation is found between the modal gain coefficient and $\Delta E/(L_p \cdot \gamma_{32})$ as shown in Fig. 2.41(c). Although it is difficult to know quantitatively the influence of $\Delta E$ on the optical gain coefficient from the above correlation plots, they nevertheless provide us with an insight on another important factor that should be taken into account when designing ultra-strong coupling QC lasers.

Apart from further optimizing the band-structure design for these ultra-strong coupling QC lasers, the device performance can also be improved from other aspects such as the waveguide (laser cavity) design. Two of the most important waveguide parameters are the mode confinement factor and the waveguide loss, because both parameters affect the threshold current density, and the waveguide loss also affects the slope efficiency as well as the optical extraction efficiency. The relatively low waveguide loss (~1.5 cm$^{-1}$) associated with wafer No. A785 is an important contributing factor to its high performance. Another important waveguide related factor affecting the device performance is the lateral mode profile. In pulsed mode operation, most high performance ultra-strong coupling QC lasers exhibit degradation of the slope efficiency and pulse instability at relatively high output power level. Such changes are usually accompanied by the broadening of the far-field profile in the lateral direction (parallel to the material layers) and sometimes higher order lateral modes are observed (an example is given in Fig. 2.42). These observations indicate that the competition between lateral modes at high power levels is a possible cause for the pulse instability and degradation of slope efficiency, and therefore should be mitigated by optimizing the waveguide design such as employing much narrower waveguide structures to suppress the emergence of higher order lateral modes.
Comprehensive optimizations of the active core as well as the waveguide designs should be employed to further improve the performance of the ultra-strong coupling QC lasers. The coupling strength has been chosen to be ~20 meV in all of our ultra-strong coupling designs; however, this value is estimated based on some material parameters that have not been directly characterized with high accuracy (such as the interface roughness average height and correlation length), and therefore it may be beneficial to experimentally investigate the optimal coupling strength in a more systematic way. Besides, additional strategies for improving the device temperature characteristic such as those studied in section 2.7 should be properly incorporated in future designs. The energy separation between the upper laser state and the lowest satellite valley in the active region should also be made sufficiently large to avoid potential current leakage into the satellite valleys. The waveguide structure should also be further optimized to reduce the waveguide loss and improve transverse mode selectivity.
References


Mid-IR Light Detection and Ranging (LIDAR) System Employing a High-power Ultra-strong Coupling QC Laser

Mid-IR QC lasers are versatile light sources for a broad range of molecular sensing applications due to the strong absorption lines of gas molecules in the mid-IR wavelength range. In addition, they also have potential applications for detection of much larger particles, such as aerosols in the atmosphere. Since aerosols of various categories in the atmosphere have crucial impact on climate and human health and are an important subject for meteorological study, QC laser based mid-IR LIDAR systems for characterizing the atmospheric aerosol profile is another highly attractive application [1-4]. For such applications, mid-IR QC lasers offer the capability of targeting larger aerosol particles more effectively than visible and near-IR lasers due to their much longer wavelength. In the mid-IR wavelength range, there are two atmospheric windows suitable for remote sensing applications such as LIDAR or open-path sensing systems [5-7], which are from 3 µm to 5 µm and from 8 µm to 14 µm, respectively. With the developed high-performance ultra-strong coupling QC lasers operating at wavelengths within the first mid-IR atmospheric window as described in Chapter 2, we have been exploring their potential for realizing a QC laser based mid-IR LIDAR system aiming at characterization of the profile of relatively large aerosol particles in the atmospheric boundary layer (planetary boundary layer), i.e. the lowest part of the atmosphere directly interacting the planetary surface; the proof-of-concept results and the up-to-date development are presented in this chapter.
3.1 Principles of LIDAR systems

A LIDAR system works in principle similarly to a radar system, in that the range of remote targets is extracted from the delay between the outgoing and returning signal, and information on certain properties of the targets are contained in the time evolution of the returning signal intensity. However, one of the most distinctive differences is that a LIDAR system makes use of light (usually light from lasers) instead of radio frequency waves or microwaves. Therefore, LIDAR systems enable much higher directionality, and by exploiting the various forms of interactions between light and matter, LIDAR systems are not only capable of detecting macroscopic objects [8], but also are more frequently used for detecting microscopic particles such as aerosols and molecules remotely [3,10], which is their unique advantage over radars.

3.1.1 Different mechanisms of light and matter interaction exploited in LIDAR systems

The interactions between light and microscopic particles mainly include several different scattering mechanisms and absorption. When the physical size of the particles is much smaller (< 1/10) than the wavelength of the light, the particles cause Rayleigh scattering to the light which is well known as the cause for the blue sky. If treating the particles as spherical objects, the intensity of the scattered light by a single particle in atmosphere in the Rayleigh scattering regime is given by [10]

\[ I = I_0 \frac{1 + \cos^2 \theta}{2R^2} \left( \frac{2\pi^4}{\lambda^4} \right) \left( \frac{n^2 - 1}{n^2 + 2} \right)^2 \left( \frac{d}{2} \right)^6, \]  

(3.1)

where \( I_0 \) is the intensity of the incident light, \( \theta \) is the scattering angle, \( R \) is the distance from the particle, \( \lambda \) is the wavelength of the light, \( n \) is the refractive index of the particle, and \( d \) is the diameter of the particle. The Rayleigh scattering of light by a molecule is due to the light-induced dipole moment of the molecule, and the scattering intensity is related to the polarizability of the molecule through [11]

\[ I = I_0 \frac{8\alpha^2}{R^2} \left( \frac{\pi}{\lambda} \right)^4 (1 + \cos^2 \theta), \]  

(3.2)
where $\alpha$ is the polarizability of the molecule. Therefore the Rayleigh scattering intensity is critically dependent on the wavelength of the light, as well as the size of the scattering particles or the property of the scattering molecules.

When the size of the particles is comparable to the wavelength of the light, the scattering of the light can no longer be described by Rayleigh scattering, instead the Mie scattering theory is applied [10]. Many types of aerosol particles in the lower portion of the atmosphere (dust, pollen, water droplets, sea salt, smoke, etc.) have diameters $\sim 1 \, \mu m$, and therefore they cause Mie scattering to visible as well as infrared light.

Rayleigh scattering and Mie scattering are both elastic scattering processes. Inelastic scattering such as Raman scattering [12] is also present in the atmosphere. Raman scattering is mainly caused by molecules, and the frequency shift between the incident light and the scattered light is a characteristic of the molecule involved. Therefore, Raman scattering can be exploited to identify the scattering molecules in the environment and is also exploited in different LIDAR systems [2,13,14].

Besides different scattering mechanisms, light can also be absorbed by particles and molecules. In fact, absorption and scattering processes are intertwined: concurrent absorption of light is associated with both Rayleigh scattering and Mie scattering processes; and Raman scattering can be considered as a process involving absorption of the incident photon followed by the emission of another photon. In addition, relatively strong absorption of light takes place when the photon energy is in resonance with specific electronic or vibrational and/or rotational transitions associated with the molecules. LIDAR systems based on molecular absorption spectroscopy have also been extensively investigated.

Due to the broad variety of interesting particles and molecules and the different exploitable interactions between light and matter, many types of lasers within a wide frequency range, from ultraviolet to mid-IR, have been employed in different types of LIDAR systems [15-19]. Mid-IR LIDAR
systems are of particular interest for the detection of large aerosol particles (diameter $\gg 1 \ \mu m$) which are abundant mainly in the atmospheric boundary layer.

3.1.2 Operation of elastic backscattering LIDAR systems

A typical LIDAR system consists of four major components for realization of its core function: a laser with a collimated beam operating in pulsed mode, a telescope for collecting the returning signal, a detector with sufficiently fast response, and a signal processing unit for analyzing the returning signal and extracting the desired information. A simplified schematic for a typical LIDAR system is shown in Fig. 3.1. When a light pulse from the laser with pulse duration of $\Delta t$ is collimated and sent out into the atmosphere at time $t_0$, it will get reflected or scattered backwards whenever it encounters a macroscopic object or passes through a plume of particles and/or molecules that causes strong enough backscattering. Here, we assume no macroscopic object is present and the return signal is entirely due to elastic backscattering (Rayleigh and Mie scattering) from microscopic particles and/or molecules. If the plume of particles and/or molecules is located in a range beginning at a distance of $H_1$ from the LIDAR, then the returning signal should reach the detector at the moment $t_1 = 2H_1/c$ where $c$ is the speed of light in the atmosphere. If the returning signal is also a pulse with a duration significantly longer than the initial laser pulse (assume it ends at $t_1'$ as shown in Fig. 3.1), then the thickness of the plume can be estimated to be $\sim(t_1' - t_1 - \Delta t)c/2$. Therefore the timing of the returning signal carries the information on the range of the target. The intensity of the returning signal also contains information on the strength of the backscattering processes, which depends on both the properties (size, polarizability, etc.) of the target particles and/or molecules as well as their concentrations. However, since the intensity of the incident light pulse is a function of its traveling distance due to the constant absorption and scattering of the light pulse before it reaches a specific location, and the backscattered light also experiences absorption and scattering on its way back to the detector, one must take these crucial factors into account when extracting information from the time
evolution of the returning signal intensity. In addition, factors such as the beam spreading and the collection efficiency of the detector also need to be included in the data analysis.

Fig. 3.1 Schematic of the operation principle of a simplified typical LIDAR system.

Fig. 3.2 Schematic of the overlap function between the laser beam and receiver field of view.

Another important factor determining the intensity of the received backscattered signal is the overlap function of the LIDAR system, which characterizes the overlap between the laser beam and the field of view of the receiver (the telescope and the detector) as a function of the distance $z$, which is schematized in Fig. 3.2. Since in most cases only the backscattered signal from locations in the long-range (>100 m) are of interest, the overlap function in the short-range is designed to be zero.
This is because the short-range backscattered signal has an intensity orders of magnitude higher than that of the long-range signal due to the quadratic decay of the backscattered signal intensity with traveling distance (e.g. Eqns. (3.1) -(3.2)) and the optical loss (scattering and absorption) experienced during traveling, while on the other hand the detector has limited dynamic range, thus if the detector responsivity is designed for the long-range signal intensity level, it will be saturated by the short-range signal. The overlap function is determined by the geometric configurations of the system. For example, in the schematic in Fig. 3.2 it depends on the following parameters: diameter of the telescope mirror $D_t$, the angle of the receiver system’s field of view $\delta_r$, the laser beam width $D_L$, the divergence angle of the laser beam $\delta_L$, the distance between the laser and the center of the telescope $D_S$, and the angle between the telescope optical axis and the laser beam $\delta_S$. However, in practice an accurate calculation of the overlap function can be challenging since it is difficult to obtain accurate values for all the required system parameters, and the overlap function is often obtained experimentally [20].

Taking all the dominant factors into account, the elastic backscattered signal detected by the LIDAR satisfies the LIDAR equation [20,22]

$$P_r(z) = P_0 \cdot \frac{c \Delta t}{2} \cdot \frac{A_T \eta_R \cdot O(z)}{z^2} \cdot \beta(z) \cdot \exp(-2 \int_0^z \sigma(z')dz'),$$

(3.3)

where $P_r(z)$ is the received power of the backscattered signal from a distance $z$, $P_0$ is the power of the outgoing laser pulse, $\Delta t$ is the laser pulse duration, $A_T$ is the area of the telescope primary mirror, $\eta_R$ is the optical loss associated with the receiver system, $O(z)$ is the aforementioned overlap function, $\beta(z)$ is the elastic backscattering coefficient at distance $z$, and $\sigma(z')$ is the extinction coefficient (including absorption and scattering processes) at distance $z$. Among all the above parameters, $P_0$, $\Delta t$, $A_T$, $\eta_R$, $O(z)$ are system parameters and therefore can be optimized to enhance the detected signal and the signal to noise ratio (SNR). Therefore, Eqn. (3.3) suggests that higher power and longer duration of the laser pulse (higher pulse energy), larger area of the telescope primary mirror, and
lower optical loss all benefit the signal detection, while the overlap function for the interested
detection range should be maximized.

However, although longer laser pulses improve the backscattered signal power, a drawback is
also incurred: the spatial resolution of the LIDAR measurement becomes lower. The limitation on the
spatial resolution of the LIDAR measurement originates from the fact that backscattered signal from
different locations within a certain range return to the receiver at the same time as a result of the finite
pulse duration. If the laser pulse is infinitesimally short, then the detected signal at any specific
moment corresponds to the backscattering at a specific location, and the spatial resolution is solely
limited by the detector’s response speed. However, if the pulse duration is $\Delta t$, then the backscattered
signal generated at the moment $t_0$ and location $z_0$ returns to the detector together with the signal
generated at the moment $t_0 + \delta t$ and location $z_0 - c \cdot \delta t$ where $\delta t \in [0, \Delta t/2]$. Therefore, the spatial
resolution of the LIDAR measurement is $c \cdot \Delta t / 2$. For example, for a pulse width of ~200 ns, the
spatial resolution is ~30 m. Thus, when determining the laser operation mode, the requirement on
spatial resolution should be taken into account.

Even with state-of-the-art laser sources and optimized system configuration, the power of the
detected backscattered signal from a very long range may still fall below the detector noise level,
therefore averaging of the signal over many pulses needs to be performed to improve the SNR. The
higher the pulse repetition rate is, the faster the averaging can be performed to reach a desired SNR.
However, the pulse repetition rate cannot be infinitely increased, it is limited by the distance range the
LIDAR measurement is targeting. If the longest distance targeted by the measurement is $L_{\text{max}}$, then
the pulse repetition rate should be set well below $c/2L_{\text{max}}$ in order to avoid any overlap of
backscattered signal within the measurement range generated from two consecutive light pulses.
3.2 Proof-of-concept demonstration of a QC laser based mid-IR backscattering LIDAR system

Mid-IR remote sensing systems demonstrated so far are mostly in the form of open-path systems, in which a retro-reflector or a solid object is used to reflect the light signal back [5,18]. The lack of highly powerful pulsed lasers in the mid-infrared wavelength range has limited the realization of mid-IR LIDAR systems based on detection of backscattered signal from particles and/or molecules which is substantially weaker than that from reflection by solid objects. As the performance of mid-IR QC lasers, more specifically the peak output power, improves rapidly in recent years, mid-IR QC laser based backscattering LIDAR systems appear to be more and more feasible [22]. In this section, we report a proof-of-concept demonstration of a backscattering LIDAR system employing the high performance ultra-strong coupling QC lasers described in Chapter 2.

Fig. 3.3 Schematic of the proof-of-concept backscattering LIDAR system design.

3.2.1 System design

A proof-of-concept backscattering LIDAR system is designed to verify whether detection of backscattered signal from aerosols at a sufficiently long distance is realizable with state-of-the-art QC lasers [23]. The schematic of the system design is shown in Fig. 3.3. For the purpose of easy aligning
and testing, the system is designed to be pointing horizontally. The entire system consists of a high-performance ultra-strong coupling QC laser operating at \( \sim 4.5 \, \mu \text{m} \), a collimation lens to collimate the fast diverging QC laser beam, a telescope for collecting and directing the backscattered signal to a focusing lens which focuses the signal into a highly sensitive detector.

### 3.2.2 QC laser characterizations and selection

A large number of QC lasers are characterized and the best ones for the LIDAR application are selected. The peak output power is an important criterion for QC laser selection process. Another crucial criterion is the beam quality of the QC laser beam, because it has substantial influence on the collimation range of the laser beam, and a well collimated laser beam is crucial for LIDAR operation (outside the collimation range the laser beam diverges rapidly, reducing the system overlap function).

A systematic study on the beam quality for QC lasers with different cavity geometry has been conducted. It is observed that the beam quality in the direction perpendicular to the epitaxial layers is similar for all the QC lasers characterized and is independent of the output power, while the beam quality in the direction parallel to the epitaxial layers critically depends on the ridge width of the QC laser as well as the output power. The beam quality is characterized by the beam propagation factor \( M^2 \) which is defined as

\[
M^2 = \frac{\pi d_0 \theta_{\text{div}}}{4 \lambda},
\]

where \( d_0 \) is the width of the beam waist, \( \theta_{\text{div}} \) is the far-field divergence angle of the beam, and \( \lambda \) is the emission wavelength. The beam waist of QC lasers can be considered to be located at the facet, therefore the widths of the beam waist in the perpendicular and the in-plane directions are approximately the height (\( \sim 8 \, \mu \text{m} \)) and the width of the laser ridge, respectively. The far-field profile of the beam is also dependent on the width of the beam waist, which explains why the beam propagation factor in the growth direction is similar across all the QC lasers.
Fig. 3.4 Far-field profiles in the vertical direction of an exemplary QC laser at output power of 0.4 W (top) and 2.1 W (bottom). An output power independent beam propagation factor of $M^2 \sim 1.6$ is extracted.

Figure 3.4 shows the characterization results of the far-field profiles in the vertical direction for a typical QC laser operated at different output power levels. The divergence angle is $\sim 68.8^\circ$, and the beam propagation factor $M^2$ is calculated to be $\sim 1.6$, very close to the ideal value of 1. Figure 3.5(a)-(c) show the characterization results of the far-field profiles in the in-plane direction for three QC lasers with different ridge widths and operated at different output power levels, and the beam propagation factors are summarized in Fig. 3.5(d). It can be seen that the beam propagation factor in the in-plane direction increases with the output power level, and that the QC lasers with ridge widths of 15.5 µm and 18.5 µm have similar $M^2$ values, and the QC laser with ridge width of 21.5 µm has a much larger $M^2$ value and worse beam quality. Therefore, the QC laser with ridge width of 18.5 µm appears to be the best choice since it has a relatively good beam quality and at the same time relatively high peak output power.
Fig. 3.5 Far-field profiles in the in-plane direction for three QC lasers with different ridge widths: (a) \( \sim 15.5 \, \mu m \), (b) \( \sim 18.5 \, \mu m \), (c) \( \sim 21.5 \, \mu m \). (d) The beam propagation factor \( M^2 \) at two different output power levels versus the ridge width of the QC lasers.

Fig. 3.6 Pulsed LIV characteristics at 80 K for the QC laser selected for the LIDAR system.
The best performing QC laser is selected among several tested devices with similar dimensions. The pulsed LIV characteristics of this laser are shown in Fig. 3.6. At 80 K, the peak output power of this laser reaches ~8.5 W. The output power can be further significantly increased if an HR coating is applied to the back-facet.

### 3.2.3 Laser beam collimation

The laser beam coming out of the QC laser facet is highly diverging as can be seen from Fig. 3.4 and Fig. 3.5, and therefore must be collimated for the LIDAR application. The simplest method for beam collimation is to use a spherical lens. However, the aberration associated with a spherical lens significantly limits the collimation range. In order to achieve longer collimation range, an aspheric lens should be used instead. The numerical aperture of the collimation lens should also be sufficiently large to capture most of the output power from the QC laser. Therefore, an AR coated ZnSe aspheric lens with 1 inch focal length and 2 inch diameter is customized for the collimation of the QC laser beam.

The collimation range of the QC laser beam using the customized aspheric lens is simulated and shown in Fig. 3.7. The collimation range is limited in the in-plane direction, since the associated beam quality is lower than that in the perpendicular direction. Nevertheless, it is sufficient for this proof-of-concept work.
3.2.4 Telescope specifications

The receiving telescope is based on a Dobsonian design (Meade 12" LightBridge Truss-Tube Dobsonian). The diameter of the primary mirror is 12 inches, and the focal length is 60 inches, therefore the ratio between the primary mirror diameter and focal length of 1:5. The schematic of the structure of the telescope can be found in Fig. 3.3. The backscattered signal is collected by the primary mirror, which focuses and directs the signal to a secondary flat mirror with the mirror surface tilted 45° with respect to the optical axis of the telescope. The secondary mirror reflects the signal beam in the direction perpendicular to the telescope optical axis out of the telescope through an aperture on the telescope sidewall. The signal beam is further focused by another spherical lens (f = 1.5 inches) on to the detector.
3.2.5 Detector specifications

A liquid nitrogen cooled Indium Antimonide (InSb) detector with high sensitivity but relatively slow response is used for detecting the backscattered signal. The specifications for the detector and its preamplifier are listed in Table 3.1.

<table>
<thead>
<tr>
<th>InSb Photodiode (peak response at 4.5 μm) Liquid N₂ cooled</th>
<th>Pre-amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detectivity*</td>
<td>Gain</td>
</tr>
<tr>
<td>1×10¹¹ cmHz¹/²/W</td>
<td>1×10⁶ (V/A)</td>
</tr>
<tr>
<td>Peak Responsivity</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>3 A/W</td>
<td>DC to 300 kHz</td>
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<tr>
<td>Acceptance angle, F/#</td>
<td>(Voltage) Noise Density @ 1kHz</td>
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<tr>
<td>60°, 1</td>
<td>6.5 nV/Hz¹/²</td>
</tr>
<tr>
<td>Active Element Diameter</td>
<td></td>
</tr>
<tr>
<td>0.25 mm</td>
<td></td>
</tr>
<tr>
<td>NEP</td>
<td></td>
</tr>
<tr>
<td>0.2pW/Hz¹/²</td>
<td></td>
</tr>
<tr>
<td>Background Current</td>
<td></td>
</tr>
<tr>
<td>0.4 µA</td>
<td></td>
</tr>
</tbody>
</table>

3.2.6 Field test results and discussions

We set up the system in a large vacant area on campus where no object is present in front of the system within ~200 meters. A photo of the field test setup is shown in Fig. 3.8. The QC laser is housed in a cryostat and kept at a temperature of ~80 K. The QC laser is operated around its maximum peak output power (~8 W per facet), driven by a pulse generator with pulse width of 100 ns and a repetition rate of 5 kHz, corresponding to a pulse energy of 0.8 µJ and an average power of ~4 mW. The output signal from the detector’s preamplifier is further fed into a lock-in amplifier with the integration time set to 100 ms.

The laser beam is collimated by imaging the projection of the laser beam onto a diffusing thin film (lens paper) with an IR camera and adjusting the optical components accordingly until the size of the projection on the thin film does not change with the distance to the laser. After collimation of the laser beam, the system is first aligned with the help of an aluminum foil with rough surface which is highly reflective in a wide range of directions, mimicking a strong elastic scatterer. The aluminum
foil target is initially held at ~10 m away from the system, and the system (e.g. the telescope and the
detector) is aligned by maximizing the detector output. Then the distance is gradually increased and
the alignment process is repeated at each distance.

Then we conduct the backscattering experiment, for which a large plume of water vapor in
the path of the laser beam is generated by pouring hot water onto dry ice, and the amplitude of the
signal registered on the lock-in amplifier is recorded and the SNR is calculated. The distance between
the plume of water vapor and the LIDAR system is gradually increased from ~5 m to ~50 m, and for
each new position of the plume, the system is realigned to maximize the received signal amplitude.

Figure 3.9 shows the obtained SNR for these measurements as a function of the distance
between the water vapor plume and the LIDAR system. Using the aspheric lens for collimation, the
SNR reaches ~50 at a distance of ~5 m and is more than 10 at a distance of ~20 m, much better than
that achieved with a spherical collimation lens (green data points in Fig. 3.9). However, such a large
contrast may not solely originate from the difference in the quality of the beam collimation, the
quality of the system alignment may also be a dominant factor since the two measurements were not conducted in the same day.

Fig. 3.9 SNR for the measurements of backscattered signal by a water vapor plume as a function of the distance between the water vapor plume and the LIDAR system. The red data points are obtained with the aspheric collimation lens, while the green data points are obtained with a spherical collimation lens.

As expected, the SNR decreases rapidly with distance and at a distance of ~50 m the SNR reduces to slightly higher than 2. However, an interesting feature in the data is that the decrease of SNR is much slower than $z^{-2}$ that would be expected according to Eqn. (3.1). This suggests another factor in Eqn. (3.3) is increasing significantly with distance in the range the measurements are conducted, and it is not difficult to see the only parameter that can have such a property is the system overlap function $O(z)$. Since the absorption and scattering of light traveling in the free space within such short range is negligible, thus if the property $\beta(z)$ associated the water vapor plume does not vary significantly across all the measurements, then at least the shape of the overlap function can be extracted from the backscattered signal versus distance data. According to Eqn. (3.3), $O(z) \propto S(z)z^2$ when the variation of all the other terms are negligible. Figure 3.10 plots the $S(z)z^2$ versus $z$ where
$S(z)$ is the backscattered signal. Therefore $O(z)$ increases significantly within the distance range of the measurements. In fact, such a trend of the overlap function can be readily perceived from Fig. 3.2.

![Graph showing product of backscattered signal and $z^2$ vs distance]

Fig. 3.10 Plot of the product of the backscattered signal and $z^2$ as a function of $z$. The trend of the data points is approximately the same as that of the overlap function $O(z)$.

Although from this field test we have only reached ~50 m range with a SNR larger than 1, significantly shorter than the desired range of a few hundred meters for LIDAR based aerosol measurements, the result is nevertheless promising because we see a lot of opportunities to greatly improve the SNR.

First of all, in the field test, the signal reading is almost real-time (the lock-in amplifier has an integration time of ~100 ms) while for most LIDAR based aerosol measurements, a signal averaging time on the scale of 10 minutes is routine. If a 15-minute signal averaging time is employed for our experiments, the SNR is expected to increase $\sqrt{15 \text{ min}/0.1 \text{s}} \approx 100$ times, that the SNR at 50 m would be around 200. If assuming the system overlap function saturates at the distance range above 50 m, then the SNR would decrease quadratically with distance, and at a distance of 500 m the SNR would be ~2 which is sufficient for LIDAR measurements.
Furthermore, the laser repetition rate of 5 kHz employed in the field test is limited by the pulse generator and can be considerably increased provided a more advanced pulse generator is available. If we are interested in the distance range of 500 m, then the pulse repetition rate can be raised to 300 kHz without significant overlap of backscattered signals from consecutive pulses. Even with a pulse repetition rate of 100 kHz which makes the overlap of backscattered signals from consecutive pulses essentially zero, the SNR is still expected to be enhanced by another 20 times.

In addition, as mentioned previously the QC laser employed in this work has as-cleaved facets on both ends. Therefore the usable peak power from this laser can be further improved by applying a HR coating on the laser back-facet. The peak power of QC lasers can also be improved by other approaches such as incorporating more stages in the laser active core.

Last but not least, the overall quality of the system alignment should also have room for further improvement, because due to the lack of very firm mechanical support (such as an optical table) and a stabilized environment in the field, the mechanical stability and the alignment of the system are affected by various factors such as wind, temperature change, and mechanical vibrations.

3.3 Design and preliminary implementation of a vertically oriented mid-IR backscattering LIDAR system for aerosol monitoring

Following the proof-of-concept demonstration of a mid-IR QC laser based LIDAR system for detection of backscattered signal from man-made aerosol, we have been developing a permanent, vertically oriented QC laser based backscattering LIDAR system aiming at characterizing the profile of relatively large aerosol particles in the atmospheric boundary layer (the lowest ~200 m range).

The basic structure of the vertically oriented system shown in Fig. 3.11 is similar to the previous horizontally oriented one. However, this new LIDAR system is designed to have a coaxial configuration, i.e., the outgoing collimated laser beam travels along the optical axis of the telescope, in order to maximize the overlap function for the entire detection range. In order to achieve such a system structure, three gold-coated mirrors are employed to direct the laser along the desired path.
Besides the orientation change, another major update of the system is related to the realization of its capability to extract the timing and thus the range information from the backscattered signal, and some key components are incorporated accordingly.

Fig. 3.11 Schematic of the vertically oriented QC laser based backscattering LIDAR system for aerosol detection and characterization.

In order to resolve the timing information of the return signal, the detector and the preamplifier has to be fast enough. The spatial and temporal resolution of the measurement is ultimately limited by the duration of the laser pulses, in order to reach such a resolution limit, the response time of the detector should be much smaller than the pulse duration and the bandwidth of the preamplifier should be much larger than the inverse of the pulse duration. The previously employed liquid nitrogen cooled InSb detector is very slow compared to the laser pulse duration, hence not
suitable for real LIDAR applications. For the new system, a thermoelectrically cooled high-sensitivity mercury cadmium telluride (MCT) detector which has response time of 15 ns is used instead.

The fast time evolution of the backscattered signal resolved by the detector needs to be further processed in real-time, including sampling, averaging and storing. A transient recorder (Licel TR40) specifically designed for LIDAR applications is employed in the system to accomplish such a task. With a sampling rate of 40 MHz, the resolution limit set by the pulse duration (≥100 ns) is well maintained in the sampling process. The transient recorder links the sampled backscattered signal to the range information of the signal by initializing the sampling process every time a laser pulse is fired and sample with a highly precise frequency. In this way, the $n_{th}$ data point sampled in a cycle corresponds to the backscattered signal generated at a distance $\sim n \times c \times 25 ns/2$ away from the LIDAR system.

Therefore, the transient recorder requires a trigger signal that is synchronized to the laser pulses in order to function properly. In our system, such a trigger signal is provided by the output of another fast response detector which monitors the firing of the light pulses. A small fraction (<5%) of the light pulses is directed to this trigger detector by an unbalanced beam splitter as shown in Fig. 3.11. The unbalanced beam splitter is essentially a CaF$_2$ window with AR coating and therefore more than 95% transmission. The residual reflection from the CaF$_2$ window is focused into the trigger detector by another lens. Besides providing the trigger for the transient recorder, the trigger detector also functions as a reference detector for monitoring the power fluctuation of the light pulses.
The system described above has been built in a lab dedicated for LIDAR measurements on the top floor of the engineering building. A hatch on the ceiling of the lab can be opened to allow firing of laser pulses vertically into the atmosphere and collecting the backscattered signal. Photos of the system are shown in Fig. 3.12. Collimation of the laser beam is achieved with similar techniques used in the field test of the horizontal system. Preliminary alignment of the entire system has been performed with solid objects placed above the hatch, and backscattering experiments have also be conducted with water vapor plumes generated on the roof next to the hatch.

Further fine alignment of the system needs to be performed, and one of the most important tasks is to ensure that the laser beam and the telescope optical axis are coaxial with high precision. A big challenge of aligning such a vertically oriented LIDAR system is that no retro-reflector or macroscopic objects can be easily placed in the path of the laser beam far away from the system to assist the alignment process. Fortunately, if the laser beam is well collimated, its high peak power may allow backscattered signal from low-lying cloud (in the range around 1 km) to be detected, facilitating the alignment of the system for long range detection.
3.4 Conclusion

In conclusion, we have evaluated and confirmed the feasibility of employing high performance ultra-strong coupling QC lasers for mid-IR backscattering LIDAR applications, and conducted proof-of-concept experiments on a QC laser based horizontally oriented backscattering LIDAR system. The detection of backscattered signal from water vapor aerosol at a distance up to ~50 m with sufficient SNR is demonstrated and various approaches for further improvement are discussed. The results are promising and encouraging. We have further designed and built a vertically oriented QC laser based backscattering LIDAR system specifically designed for characterizing the profile of large aerosol particles in the atmospheric boundary layer which has significant impact on the climate and human health. Preliminary system alignment has been performed, and the system is undergoing further optimization.
References


Chapter 4

Single-mode Quantum Cascade Lasers Employing Monolithic Coupled-cavities

4.1 Motivation for single-mode QC lasers

Single-mode operation of QC lasers is essential for most absorption-spectroscopy-based high-sensitivity molecular sensing applications [1-9]. In the simplest form of such a molecular sensing system (see the schematic in Fig. 4.1), the wavelength of the light emitted by the single-mode QC laser is precisely tuned to match a particular narrow absorption line of the target gas molecule; there are usually many absorption lines associated with a specific molecule within a narrow wavelength range, and considerations such as the relative strength and isolation from absorption lines of other molecules present in the environment are usually taken into account when selecting a specific absorption line for spectroscopy applications. Therefore as the light from the QC laser travels through a gas sample of concern which contains the specific type of molecules, it gets absorbed by the target molecules and the absorption is dependent on both the concentration of the target molecules and the path length of the light within this gas sample according to the Beer-Lambert Law [10] (assuming the concentration of the target molecules is uniform within the concerned region, and no absorption of light occurs outside this region)

\[ A = 1 - T = 1 - \frac{P}{P_0} = 1 - \exp(-\sigma c L), \]  

where \( A \) is the absorption, \( T \) is the transmission, \( P_0 \) is the output optical power from the QC laser, \( P \) is the optical power of the laser light after passing through the target region, \( \sigma \) is the absorption cross-section of the target molecule, \( c \) is the concentration of the target molecule and \( L \) is the path length of the light within the gas sample. The absorption cross-section \( \sigma \) of the target molecule is usually a
known parameter which can be obtained from databases such as the HITRAN database; the path length of the laser light within the region of interest can be readily measured; thus if both the laser output optical power \( (P_0) \) and the optical power after the laser light pass through the region of interest \( (P) \) can be measured accurately, the concentration of the target molecule can be calculated.

![Fig. 4.1 Schematic of an absorption spectroscopy based molecular sensing system with a QC laser as the light source.](image)

However, if the QC laser is not operating in single-mode but in multi-mode manner, i.e., it emits light not only at the wavelength (mode) that matches the specific narrow absorption line of the target molecule, but also at other wavelengths (modes) with comparable power levels, then Eq. (4.1) can no longer be applied to calculate the concentration of the target molecule. Although in principle we may still be able to extract the concentration information of the target molecule by further measuring the relative power levels of all the lasing modes, in practice this is not a feasible solution since it requires at least a spectrometer which would be very costly, the relative power levels of all the lasing modes can have complicated dynamics during the laser operation, and some of the modes may also match absorption lines of different molecules in the mixture. Therefore, employing single-mode and tunable QC lasers as the light sources for absorption spectroscopy based molecular sensing systems is by far the most straightforward and practical solution.
4.2 Brief review of different types of single-mode QC lasers

As mentioned in Chapter 1, the most straightforward QC laser cavity is a FP type resonator consisting of a simple ridge structure as the waveguide to confine the traveling light and an as-cleaved crystal plane (facet) at each end of the ridge waveguide as the partially reflecting mirrors of the cavity. However, due to the lack of wavelength selectivity of a typical FP cavity for QC lasers (1~5 mm in length) and the broad QC laser optical gain spectrum, spatial hole burning or other laser instability dynamics [11, 12] are not effectively suppressed in such simple ridge QC lasers, and the lasers generally operate in multiple modes even close to the threshold current. Although FP type QC lasers are relatively easy to fabricate with standard III-V semiconductor fabrication technologies and have high fabrication throughput and yield, and therefore relatively low cost, they are not suitable for most molecular sensing applications. Only in certain special situations a FP cavity QC laser can operate in single mode. For instance, if one makes the FP cavity extremely short ( < 200 µm) so that the spacing between neighboring FP modes are dramatically increased compared to that of typical FP cavity for QC lasers [13, 14], and if also the gain spectrum of the QC laser is relatively narrow [15], then enough gain discrimination between neighboring FP modes can be achieved, and as a consequence the QC laser operates in a single mode. However, in addition to the small size of such short cavity QC lasers which limits the input current range, the threshold current density is on the other hand much higher than QC lasers with typical cavity length, and therefore their output optical power is considerably limited.

In order to achieve high-performance single-mode operation in QC lasers despite the broad optical gain spectrum, strong wavelength selectivity needs to be introduced into the laser cavity. One way to establish strong wavelength selectivity is to make use of periodic or quasi-periodic feedback structures for strong, frequency dependent optical feedback. In fact, this kind of wavelength selectivity mechanism is prevalently employed in both research and industrial communities in the QC laser field. Such a periodic feedback structure can either be integrated into the QC laser cavity, e.g.,
integrating distributed feedback (DFB) gratings [16, 17], distributed Bragg reflectors (DBR) [18] or photonic crystals [19, 20] into the laser waveguides, or it can be employed as an external wavelength filter, e.g., an external cavity QC laser module making use of diffraction gratings to select a specific wavelength for optical feedback into the QC laser gain medium [21, 22].

Single-mode QC lasers employing DFB gratings, DBRs or photonic crystals are compact semiconductor devices similar to simple ridge QC lasers. However, the fabrication processes of such devices are more complicated and time-consuming due to the need for defining high-quality sub-wavelength periodic structures, and often require more advanced fabrication techniques such as e-beam lithography or focused-ion-beam milling. In addition, in these single-mode lasers, the optical feedback from the end facets or boundaries of the laser cavity is detrimental for the single-mode operation, hence additional measures such as applying anti-reflection coatings or absorbing device boundaries are highly desired for eliminating such optical feedback [23, 24]. Achieving perfect anti-reflection coatings or absorbing device boundaries is not trivial, and the parasitic optical feedback may still deteriorate the spectral purity. Therefore, the fabrication cost of these devices is usually much higher than that of the simple ridge QC lasers, and a lower single-mode device yield is often an issue as well.

Another important performance specification for single-mode QC lasers is the wavelength tunability. For DFB gratings, DBRs and photonic crystals, the built-in periodicity of these structures determines the wavelength selectivity. Thus, once the structures are fabricated, the associated wavelength selectivity is relatively fixed; tuning of the lasing wavelength can be achieved by changing the refractive indices of the waveguide materials but is rather limited to a few wavenumbers [25]. On the other hand, with external cavity QC laser configuration in which a simple ridge QC laser functions mainly as the gain medium, a much larger wavelength tuning range can be achieved thanks to the flexibility of adjusting the position and the orientation of the external diffraction gratings and thus the feedback wavelength, while the tuning range is ultimately limited by the width of the optical gain spectrum of the QC lasers [26, 27]. However, in order to maximize the wavelength tuning range,
an excellent anti-reflection coating also needs to be applied to the laser facet through which the light is coupled into and out of the gain medium for the interaction with the diffraction gratings. If the reflectivity of the anti-reflection coating is not essentially zero, a FP cavity forms between the facets of the simple ridge QC laser which is detrimental to the single-mode wavelength tuning range, since at certain operating conditions the lasing modes associated with this FP cavity reach threshold before the mode selected by the external diffraction gratings; then mode-hops or multi-mode operation would occur. Developing and reliably applying a nearly perfect anti-reflection coating across a relatively broad wavelength range is a challenging task, thus this step also significantly increases the fabrication complexity of the laser chips for external cavity QC lasers. Besides, a robust optical alignment of the whole system which consists of the QC laser chip and all the other optical components including the movable diffraction gratings is also highly demanding and time-consuming. Therefore, the component and time cost of making a single-mode external cavity QC laser is even higher than that of aforementioned single-mode QC lasers employing integrated sub-wavelength scale periodic gratings.

Currently, the high cost of single-mode QC lasers is one of the most crucial issues that hinder the potential large-scale commercialization of QC laser based sensing systems in various fronts. With existing technologies, the need for sub-wavelength scale structures or external wavelength selecting systems would almost unavoidably require complicated and expensive fabrication and/or system integration steps. With such major contributions to the cost, commercially available single-mode QC lasers are mainly DFB or external cavity QC lasers, both are much more expensive than multi-mode FP cavity QC lasers.

In order to drastically address this issue, we need to fundamentally change the approach to achieving single-mode operation in QC lasers. The key question is, are there any other ways to introduce strong wavelength selectivity without the need for sub-wavelength scale periodic structures or external components? Fortunately, the answer is, yes! In this thesis two approaches, which are fundamentally different yet bear a certain degree of similarity, of realizing strong wavelength
selectivity in FP cavities are proposed and experimentally investigated and verified. The first approach is to make use of a novel form of coupled-cavity structures which are in a monolithic configuration [28, 29], and the details will be covered in the following sections of this chapter. The second approach is to integrate an asymmetric Mach-Zehnder (MZ) interferometer type structure into the FP cavity where the wavelength selectivity originates from the asymmetry of the MZ interferometer [30], and the details will be covered in Chapter 5. More importantly, both approaches enable implementations of cavity structures that can be fabricated in the same way as simple ridge QC lasers, and therefore have the potential advantage of producing single-mode QC lasers with high throughput, high yield, and low cost. This is the most crucial advantage for both approaches from the technological perspective.

Fig. 4.2 (a) Schematic of a cleaved-coupled-cavity consisting of two FP cavities with different cavity lengths. (b) Schematic of the wavelength selectivity associated with a cleaved-coupled-cavity.
4.3 Principles of coupled-cavity

The simplest form of a coupled-cavity is a cleaved-coupled-cavity, in which two FP cavities with equal cross-section placed along the same optical axis side by side, with one partial reflecting mirror from each cavity facing each other with a negligible gap (compared with the wavelength of the light) in between, as is shown in the schematic in Fig. 4.2(a). In such a configuration, light bouncing back and forth inside one cavity transmits through the partial reflecting mirrors and couples into the other cavity and vice versa. Therefore the profile of the electro-magnetic (EM) field of a particular FP mode in one cavity also depends on how it propagates in the other cavity and couples back. If the EM field of a particular FP mode of the left cavity (cavity length L₁) couples back after a round trip in the right cavity (cavity length L₂) with a phase difference of a multiple of 2π, then the field components (F₁, F₂ and so on) would constructively interfere with each other, and this is equivalent to an enhanced reflectivity of the partial reflecting mirror A. However, if for a different FP mode of the left cavity this phase difference is an odd multiple of π, then destructive interference occurs among the field components (F₁, F₂ and so on) and this is equivalent to a reduced reflectivity of the partially reflecting mirror A. We can consider the case of constructive interference as the particular mode experiencing a maximal mirror reflectivity, and the case of destructive interference as experiencing a minimal mirror reflectivity. When the phase difference falls in between the two extremes for some other modes, the mirror reflectivity also falls in between the minimum and the maximum accordingly. From this point of view, a cleaved-coupled-cavity composed of two FP cavities can be construed as using the second FP cavity to spectrally modulate the reflectivity of the partial reflecting mirror of the first FP cavity, through which light is coupled in and out. Therefore, the mirror loss associated with the first FP cavity is effectively spectrally modulated in this way, and if this effective mirror loss discrimination among neighboring FP modes situated around the peak of the optical gain spectrum is large enough, single-mode lasing can be realized as is schematically illustrated in Fig. 4.2(b).
The above qualitative analysis of a simple coupled-cavity system allows us to gain some insight on how the wavelength selectivity arises. Nevertheless, a more rigorous mathematical description is necessary for our understanding of how well it will work and how to properly design such a coupled-cavity. Still focusing on the simplified cleaved-coupled-cavity system in Fig. 4.2(a), the key is to calculate the spectrum of the effective reflectivity of mirror A due to the existence of the second FP cavity. Assuming light coupled into the second FP cavity will bounce back and forth between mirror A’ and mirror C infinite times, and after each round trip in the second cavity it hits mirror A’ once and a fraction of it is coupled back into the first cavity, therefore to calculate the effective mirror reflectivity we need to calculate the superposition of all the infinite number of field components that are coupled back. Furthermore let’s assume that the refractive index is unity everywhere and there is no loss when light propagates, the gap between mirror A and A’ is negligible and thus the two mirrors can be considered as one mirror AA’ with an combined reflectivity $R_A$, the reflectivity of mirror C is $R_C$, and the lengths of the first and the second cavities are $L_1$ and $L_2$, respectively. When a plane EM wave with wavenumber $k$ and electric field (E-field) amplitude $F_0$ is launched perpendicular towards mirror AA’ from the left, the reflected wave from mirror AA’ has E-field amplitude $F_1 = \sqrt{R_A}F_0$ and a phase difference $\pi$ with respect to the incident wave (the reflection on the mirror introduce a $\pi$ phase shift). The wave coupled into the second cavity has an E-field amplitude $\sqrt{1-R_A}F_0$, and when it returns after a round trip of length $2L_2$ in the second cavity, it partially couples back to the first cavity through mirror AA’ with E-field amplitude $F_2 = (1 - R_A)\sqrt{R_C}F_0$ and a phase difference of $4\pi k L_2 + \pi$; after the second round trip the back coupled wave has E-field amplitude $F_3 = (1 - R_A)\sqrt{R_A R_C}F_0$ and a phase difference of $8\pi k L_2 + 3\pi$; and after the n-th round trip the back coupled wave has E-field amplitude $F_{n+1} = (1 - R_A)\sqrt{R_A}^{n-1}\sqrt{R_C}^{-n}F_0$ and a phase difference of $4n\pi k L_2 + (2n + 1)\pi$. Therefore, the E-field component of the superposition of all the lightwaves coupled back from the second cavity to the first cavity is
\[
\sum_{i=1}^{\infty} F_i = F_1 + \sum_{i=2}^{\infty} F_i = \sqrt{R_A} \exp(i \pi) F_0 + \frac{(1 - R_A) \sqrt{R_C} \exp(i 4 \pi k L_2 + \pi)}{1 - \sqrt{R_A R_C} \exp(i 4 \pi k L_2)} F_0.
\]

(4.3)

The effective reflectivity of the mirror AA’ due to the existence of the second FP cavity is given as

\[
R_{\text{eff}}(k) = \left| \frac{\sum_{i=1}^{\infty} F_i}{F_0} \right|^2 = 1 - \frac{(1 - R_A)(1 - R_C)}{1 + R_A R_C - 2 \sqrt{R_A R_C} \cos(4 \pi k L_2)}.
\]

(4.4)

Clearly, \( R_{\text{eff}} \) is a periodic function of the wavenumber \( k \) of the incident wave (in fact, it is much easier to derive Eqn. (4.4) by first calculating the effective transmission coefficient from summing up the field components of the lightwaves going out of mirror C in Fig. 4.2(a)), and examples of the spectra of the effective mirror reflectivity \( R_{\text{eff}} \) with various values for \( R_A \) and fixed \( R_C = 0.3 \) (typical mirror reflectivity for an as-cleaved facet of mid-IR QC lasers) are plotted in Fig. 4.3. Thus, the effective reflectivity of mirror AA’ is spectrally modulated in a periodic fashion by virtue of the second FP cavity, with the modulation periodicity determined by the cavity length \( L_2 \), and the modulation depth determined by the intrinsic reflectivity of mirror AA’ and mirror C. All of these parameters can be readily manipulated so that a desired wavelength selectivity can be obtained to facilitate single-mode operation of the lasers.
Fig. 4.3 Calculation of the effective reflectivity spectra of mirror AA’ in the wavenumber range 2000 cm⁻¹ to 2050 cm⁻¹, assuming $L_2 = 1$ mm, $R_C = 0.3$, and $R_A = 0.5$ in (a), 0.1 in (b), and 0.01 in (c), respectively.
Fig. 4.4 Calculation of the effective mirror loss of mirror AA’ in the wavenumber range 2000 cm\(^{-1}\) to 2050 cm\(^{-1}\), assuming \(L_2 = 1\) mm, \(R_C = 0.3\), and \(R_A = 0.5\) in (a), 0.1 in (b), and 0.01 in (c), respectively.
The effective mirror loss associated with mirror AA’ which is determined by the effective mirror reflectivity is also spectrally modulated. The effective mirror loss corresponding to the effective reflectivity spectra in Fig. 4.3 is plotted in Fig. 4.4. It is worth noting that even for a very small intrinsic reflectivity of mirror AA’, e.g. $R_A = 0.01$, the modulation depth in the effective reflectivity and the effective mirror loss are still significant as can be seen in Fig. 4.3(c) and Fig. 4.4(c), respectively. Recall that the first cavity has a set of FP modes with the FSR in wavenumbers of $1/(2L_1)$. If $L_1$ is different from $L_2$, the modulation periodicity $1/(2L_2)$ of the effective mirror loss is different from the FSR of the first cavity, then different FP modes associated with the first cavity experience different effective mirror loss with significant discriminations, therefore, only the FP modes that almost coincide with a particular valley of the effective mirror loss would reach the laser threshold condition first as the optical gain is increased. Conceivably, within a certain wavelength range there can be multiple FP modes coinciding with a particular effective mirror loss valley due to the periodicity of both the FP mode distribution and the effective mirror loss spectrum. However, since the optical gain has a finite spectral width and is not uniform, only the FP modes that are around the peak of the optical gain spectrum would reach the laser threshold first and consequently clamp the gain to prevent other modes from lasing. Thus, if the cavity design parameters are properly chosen so that the spectral distance between FP modes at the valleys of the effective mirror loss is large enough to introduce a significant gain discrimination, and the effective mirror loss discrimination between neighboring FP modes is also sufficient, single-mode operation can be achieved. Although in reality the structure of a coupled-cavity can be more complicated and the mode selection mechanism involves more details, such that numerical simulation is necessary for obtaining accurate descriptions, analyses similar to the above nevertheless serve as good guidance in the cavity design process.

According to the above analysis, one of the most important goals when designing a coupled-cavity is to ensure that the spectral distance between the FP modes experiencing the lowest effective mirror loss is large enough compared to the width of the optical gain spectrum. In general this can be
achieved in two scenarios: (1) a nearly balanced coupled-cavity, i.e., the two individual FP cavities have different but similar lengths; (2) a significantly unbalanced coupled-cavity, i.e., one of the FP cavities is much shorter than the other. In the first scenario, the FSR of the first FP cavity and the modulation periodicity of the effective mirror loss due to the second FP cavity is relatively small, so if a particular FP mode coincides with a valley of the effective mirror loss, the next FP mode will have a small misalignment ($|k_1-k_2|$) from the closest effective mirror loss valley. Such a misalignment first increases but then decreases as the concerned FP mode becomes farther away from the initial FP mode. The next FP mode that approximately coincides with another reflectivity peak is about $k_1k_2/|k_1-k_2|$ away from the initial FP mode (Fig. 4.5(a)) which is much larger than both $k_1$ and $k_2$. In the second scenario, if we treat the shorter cavity (cavity length $L_2$) as the effective mirror loss modulator, then the modulation periodicity is much larger than the FSR associated with the much longer cavity (cavity length $L_1$), and therefore the shorter cavity essentially functions as a mode filter which selects a small fraction of the FP modes of the longer cavity with large spacing of approximately $1/(2L_2)$ between the neighboring selected modes (Fig. 4.5(b)). In this case, the major role of the longer cavity is providing sufficient optical gain.
Fig. 4.5 (a) Schematic of the FP mode selectivity of a nearly balanced coupled-cavity. (b) Schematic of the FP mode selectivity of a significantly unbalanced coupled-cavity.

Fig. 4.6 Schematic of a monolithic coupled-cavity building block exploiting the mode mismatch and consequently the light reflection at the boundary between a straight waveguide and a curved waveguide.

The cleaved-coupled-cavity described above is conceptually straightforward, however, in practice it is not very straightforward to implement. The realization of such a cleaved-coupled-cavity requires either aligning two individual cavities with high precision (sub-micrometer resolution) or reliably cutting a fixated cavity into two separate ones with good facet quality using techniques such as focused ion beam milling [31]. Both approaches are technically challenging and thus are not realistic solutions to fabricating QC lasers cost-effectively. In order to realize coupled-cavity structures with relatively simple device fabrication, we propose to make use of the monolithic structures like the one shown in Fig. 4.6, which essentially consists of a straight waveguide connecting to a curved waveguide with relatively small bending radius. Due to the curvature difference, light propagates in the straight waveguide and in the curved waveguide with different transverse mode profiles and experiences different modal refractive indices, therefore reflection of light takes place at the geometrical boundary [32]. In this way, though having no physical boundaries in between, the two different sections function as individual cavities, yet their combination forms a coupled-cavity. By applying this idea, we can design various coupled-cavity structures with the building block illustrated in Fig. 4.6 to facilitate single-mode operation. A key technological
advantage for such monolithic coupled-cavity structures is that their fabrication processes are identical to those for simple ridge lasers.

### 4.4 Designs and fabrication of hair-pin shaped monolithic coupled-cavities for QC lasers

Employing the building block of the monolithic coupled-cavities of Fig. 4.6, we have investigated a number of different designs with various cavity shapes. Folded FP cavity structures are first implemented. Figure 4.7 shows the schematic of such folded FP cavities which consist of two parallel straight sections of equal length connected on one end by a much smaller half-ring section (with a bending radius of less than 100 µm), while the other end of the straight sections is an as-cleaved crystal plane, forming the laser facets. The entire cavity looks like a “hairpin” or an elongated half-racetrack [33]. Because the transverse waveguide modes in the two straight sections and the half-ring section have significant spatial mismatch and different modal refractive indices, the propagating light in the cavity gets partially reflected at the geometrical boundaries between the straight sections and the half-ring section. From the large spatial mismatch between the transverse modes in different sections, it is reasonable to assume the reflectivity associated with such light reflections at the geometrical boundaries between different sections to be significantly larger than 0.01, which is sufficient for introducing significant effective mirror loss modulation (see Fig. 4.4(c)). The accurate reflectivity values can be calculated based on more comprehensive waveguide modeling [34] which are beyond the scope of this work. The three sections, though having no physical boundaries in between, can be seen as individual cavities and together form a monolithic coupled-cavity with much enhanced mode selectivity.

The entire hair-pin shaped cavity is designed to have a total cavity length similar to typical simple ridge QC lasers as well as the typical ridge width, however, the physical size of the half-ring section is designed to be much smaller in order to make sure sufficient transverse mode mismatch and the difference in the refractive indices can be achieved. Therefore, such cavity designs belong to the significantly unbalanced coupled-cavity category, and the half-ring section has considerably larger
FSR than the straight sections and functions as a highly selective mode filter. The major function of the straight sections is to provide sufficient optical gain.

Fig. 4.7 Schematic of the “hair-pin” shaped folded FP cavities.

Four different “hair-pin” shaped folded FP cavities are designed with the diameter of the half-ring section varied from 50 µm to 125 µm (measured from the center of the ridge) with a step size of 25 µm. Light travels in the half-ring section in so-called “Whispering Gallery” (WG) modes which have well defined mode distributions, and each WG mode is described by a radial mode profile and an azimuthal mode profile [35]. Due to the small diameter of the half-ring section, for WG modes with the same order of radial mode, the azimuthal modes have a comb-like spectrum with a large FSR which is estimated to be varying from ~15 cm⁻¹ to ~40 cm⁻¹ for the different cavity designs, corresponding to high wavelength selectivity of the coupled-cavity. However, in reality there can be more than one radial mode involved in the light propagation in the half-ring section, each of which is related to a separate comb of azimuthal mode, therefore the cavity wavelength selectivity may be significantly lower than what is expected from single-radial-mode operation. The length of the straight sections is designed to vary from 1 mm to 2 mm and is determined in the facet cleaving process. The ridge width is designed to be ~18 µm.

QC lasers with the hair-pin shaped folded FP cavities are fabricated from QC laser material with an emission wavelength of ~4.5 µm. The design of the laser active core employs the ultra-strong
coupling concept and has been described in Chapter 2 (similar to A785). The ridge structures of the designed cavities are patterned by photolithography and wet etched through the epitaxial layer with \( \sim 8 \, \mu \text{m} \) in height and \( \sim 18 \, \mu \text{m} \) in width; SiO\(_2\) (~3000 Å) is deposited using plasma-enhanced chemical vapor deposition for electrical insulation; contact windows on top of the entire cavity are opened using reactive-ion etching; top Ti/Au (~300/3000 Å) metal contact is deposited with electron-beam evaporation; the substrate is then thinned to \( \sim 200 \, \mu \text{m} \) and bottom Ge/Au (~300/2000 Å) metal contact is deposited by electron beam evaporation. Devices with various half-ring diameters are cleaved to form the facets as well as to define the length of the straight ridges (varying from 1 mm to 2 mm) and then mounted epitaxial side up to copper heat sinks. The flow chart of the device fabrication and packaging processes is shown in Fig. 4.8. An optical microscope image and a SEM image of several fabricated device is shown in Fig. 4.9.

![Flow chart of fabrication and packaging processes](image)

**Fig. 4.8** Flow chart of the fabrication and packaging processes for the hair-pin shaped monolithic coupled-cavity QC lasers.
Fig. 4.9 (a) Optical microscope image of 4 fabricated QC lasers with 4 different hair-pin shaped monolithic coupled-cavity designs. (b) SEM image of a fabricated hair-pin shaped monolithic coupled-cavity QC laser.

4.5 Characterization results for QC lasers with hair-pin shaped monolithic coupled-cavities

Spectra of a large number of fabricated QC lasers with various half-ring diameters and ridge lengths are characterized with FTIR. The QC lasers are operated in pulsed mode with pulse width of 15 ns and a repetition rate of 80 kHz, and mostly at 80 K. Several lasers are also characterized at various heat-sink temperatures to investigate the temperature induced wavelength tuning effect. Spectra of most tested devices show strong suppression of the comb-like FP modes, they either operate in single mode or have only a few modes. Single-mode operation (with 15 dB side mode suppression ration (SMSR) as the benchmark for single-mode operation) is achieved for all the different half-ring designs. The yield for single-mode devices is also studied from the relatively large number of devices tested.
Fig. 4.10 (a) Normalized spectrum a single-mode QC laser with half-ring diameter of 100 µm and cavity length of ~1.2 mm. (b) Spectrum in (a) plotted in log-scale. (c) Normalized spectrum at single-mode QC laser with half-ring diameter of 50 µm and cavity length of ~1.1 mm. (d) Spectrum in (c) plotted in log-scale. (e)-(f) Spectra of a non-single-mode QC laser with half-ring diameter of 50 µm and cavity length of ~1.1 mm operated at 1.2I_\text{th} (e) and 1.6I_\text{th} (f), respectively.
Figure 4.10 (a)-(b) shows in linear and logarithmic scales the normalized spectra of a laser with half-ring diameter of 100 µm and straight ridge length of ~1.2 mm when operated at 80 K in pulsed mode. This laser emits in single mode up to ~400 mA above the threshold current ($I_{th}$~1.1 A) with a SMSR of up to 27 dB, and the emission wavelength is at the peak of the EL (~2240 cm$^{-1}$) measured at the same current density (2.5 kA/cm$^2$). Figure 4.10(c)-(d) shows in linear and logarithmic scales the normalized spectra of another laser with half-ring diameter of 50 µm and straight ridge length of ~1.1 mm when operated at 80 K in pulsed mode. This laser emits in single mode up to ~300 mA above the threshold current ($I_{th}$~1.0 A) with a SMSR of up to 25 dB. Figure 4.10(e)-(f) shows in logarithmic scale the normalized spectra for a non-single-mode laser with half-ring diameter of 50 µm and straight ridge length of ~1.1 mm when operated at 80 K in pulsed mode at two different pump current. The spectra show only two dominant modes from the threshold current ($I_{th}$~1.1 A) up to 1.7 A pump current, and 5 dominant modes at ~1.9 A pump current. Some of these modes are separated by large and non-equal distances which can be attributed to the WG mode distribution of the half-ring section, suggesting that more than one radial mode are involved. On the other hand, some other modes are separated by a small distance which exactly corresponds to the FSR associated with the length of the straight sections (see Fig. 4.10(f)), serving as a direct evidence that the different waveguide sections indeed function as individual cavities and together they form a coupled-cavity configuration.

Most of the single-mode lasers show at least 100 mA single-mode operating current range at 80 K (the threshold current ranges from 1.0 A to 1.5 A for most lasers), one of them has a ~800 mA single-mode operating current range and two others ~600 mA (an example is shown in Fig. 4.11). Regardless of straight ridge length, 23 out of 41 tested lasers with the smallest half-ring diameter (50 µm) operate in single mode, and 4 out of 14 tested lasers with the second smallest half-ring diameter (75 µm) operate in single mode. However, the single-mode yield is lower for lasers with larger half-ring diameters (100 µm and 125 µm). On average, devices with smaller half-ring
diameters (50 µm and 75 µm) show larger single-mode operating current range than devices with larger half-ring diameters (100 µm and 125 µm).

Fig. 4.11 Spectra of a single-mode QC laser with 50-µm half-ring diameter and 1.2-mm cavity length operated at various pump currents. Single-mode operation is achieved over more than 600 mA.

For most sensing applications it is crucial that the emission wavelength of the single-mode QC lasers can accurately hit the desired target and is tunable around it. For these hair-pin shaped monolithic coupled-cavity lasers, such a requirement can be met with the combination of tailoring the length of the straight ridges and tuning the operating heat-sink temperature. The emission wavelength is dependent on the threshold condition [36], which in turn is closely related to the straight ridge length. Figure 4.12 shows the single-mode spectra of five hair-pin shaped monolithic coupled-cavity lasers with the same half-ring diameter but different straight ridge lengths. By varying the straight ridge length from ~1 mm to ~2 mm, the threshold current density is tuned from ~2.6 kA/cm² to
~1.9 kA/cm² and ~40 cm⁻¹ emission wavelength shift is achieved. This wavelength shift is faster than the tuning of the gain spectrum with current density (~15 cm⁻¹/kA), because it is a combined effect of both the shift of the optical gain spectrum and the change in the cavity mode distribution. Figure 4.13(a) shows the spectra of another single-mode laser at various operating heat-sink temperatures and Fig. 4.13(b) plots the emission wavelength versus heat-sink temperature within the range from 80 K to 237 K. More than 15 cm⁻¹ overall tuning range is achieved; the laser operates in single mode within a large part of the entire temperature tuning range and a maximum continuous, mode-hop free single-mode tuning range of ~7 cm⁻¹ is achieved from 110 K to 170 K. It is worth pointing out that at several temperatures where the laser does not operate in single mode, the mode spacing between the two dominant lasing modes is ~1.3 cm⁻¹, corresponding to the FSR of a FP cavity with length of the straight section (~1.14 mm). Such an observation on the mode behavior again suggests that the entire cavity structure indeed functions as a coupled-cavity. The mode-hop over ~12 cm⁻¹ observed at the heat-sink temperature of 235 K originates from hopping between two WG modes associated with the half-ring structure.

Fig. 4.12 Spectra of 5 single-mode hair-pin shaped monolithic coupled-cavity QC lasers with the same half-ring diameter (50 µm) but different straight ridge length (varying from ~1 mm to ~2 mm) as indicated operated in pulsed mode at 80 K close to the threshold current.
Fig. 4.13 (a) Spectra of a single-mode hair-pin shaped monolithic coupled-cavity QC laser with 50 µm half-ring diameter and ~1.14 mm straight ridge length operated in pulsed mode close to the threshold current and at various heat-sink temperatures. (b) Plot of the emission wavelength (single-mode or double-mode) vs. heat-sink temperature from 80 K to 237 K.

Fig. 4.14 Pulsed LIV characteristics at various heat-sink temperatures for the same laser in Fig. 4.13.
The pulsed LIV characteristics of the same laser as in Fig. 4.13 at various heat-sink temperatures are given in Fig. 4.14. The threshold current density at 80 K is more than 2 kA/cm², much higher than that of a simple ridge FP cavity laser fabricated from the same wafer and comparable in total cavity length (~2.4 mm). This is also true for other characterized hair-pin shaped monolithic coupled-cavity QC lasers which have threshold current density about 3 to 4 times that of the corresponding simple ridge lasers, and their slope efficiency is also significantly lower. The high threshold current limits the maximum operating temperature and prohibits CW operation of the lasers.

Such high threshold current density indicates that some significant additional loss mechanism is associated with the designed hair-pin shaped monolithic couple-cavities. There are at least three possible origins for such additional loss: bending loss of the half-ring section [37], higher waveguide loss of the half-ring section due to the stronger interaction between the WG modes and the outer sidewall contact metal, and mode coupling loss between the straight waveguide section and the half-ring section due to the spatial mismatch of the transverse modes [38]. Additional measurements confirm that there is negligible light radiation from the half-ring section of the cavity, hence the bending loss should not be substantial. In order to investigate the significance of the higher waveguide loss of the half-ring section, we have also fabricated lasers without depositing metal onto the outer sidewall of the half-ring section (Fig. 4.15). A significant number of such QC lasers are characterized and compared to those with outer sidewall metal contact. They exhibit similar single-mode performance, and on average only slightly (~5%) lower threshold current density is observed in the lasers without the outer sidewall metal contact, which suggests that the additional waveguide loss introduced by the WG modes penetrating more into the outer sidewall and interacting with the metal contact in the half-ring section is also not significant. On the contrary, the transverse mode coupling loss between a straight waveguide and a curved waveguide with large curvature can be very large. As will be seen from the detailed discussions later in this chapter, the contribution from such mode coupling loss to the laser threshold current density is estimated to be comparable or even larger than
that from the mirror loss for the designed cavity structures. Further cavity design optimization is necessary for dramatically reducing such high mode coupling loss.

Fig. 4.15 (a) SEM image of part of a hair-pin shaped monolithic coupled-cavity QC laser without the half-ring outer sidewall covered by the metal contact. (b) SEM image in higher magnification of the transition region between the straight section and the half-ring section.

4.6 Designs of candy-cane shaped monolithic coupled-cavities

A straightforward way to reduce the threshold current density contribution from the mode coupling loss between the straight waveguide sections and the curved waveguide sections in such monolithic coupled-cavity QC lasers is to reduce the number of regions where such coupling takes place. A hair-pin shaped cavity described above has two interfaces between the two straight waveguide sections and the half-ring section. However, since the wavelength selectivity is mostly from the much smaller half-ring section and the two straight sections are nominally identical, the wavelength selectivity should not be affected significantly if only one straight waveguide is employed to form a coupled-cavity with the half-ring section with structures similar to the schematic shown in Fig. 4.16. In such “candy-cane” shaped cavity structures only one interface between the straight section and the curved section exists, therefore the total mode coupling loss associated with the whole cavity can be significantly reduced. Another concurrent advantage for such cavities is that only one laser front-facet is present, i.e., the open end of the straight waveguide section, while the hair-pin
shaped cavities have two closely separated front-facets. Single-facet cavity geometry is ideal for many applications where a well-shaped laser beam is required.

Fig. 4.16 Schematic of a candy-cane shaped monolithic coupled-cavity.

Fig. 4.17 Sematics of the 4 different type of candy-cane cavity designs.

The candy-cane shaped cavity geometry shown above in Fig. 4.16 also allows for more flexibility in the design of the curved section. For example, spiral structures consisting of multiple interconnected arcs with different curvatures can be employed to further enhance the wavelength selectivity of the coupled-cavity. Following this idea, a number of candy-cane shaped monolithic coupled-cavity designs with different spiral structures are realized. Four different types of spiral structures are designed, which have the shape of $90^\circ$, $180^\circ$, $360^\circ$ and $540^\circ$ turning angles, respectively, (see Fig. 4.17). The $90^\circ$ and the $180^\circ$ spirals are essentially a quarter ring and a half ring, respectively;
the 360° and the 540° spirals consist of two and three half rings of different radii connected together. For each type of spiral structure, a number of different geometries, i.e. different radii, are evaluated and the details are listed in Table 4.1.

Table 4.1 Geometry details for the 4 different spiral structures
(The numbers are the diameters of the individual arcs that form the spirals, from outer to inner.)

<table>
<thead>
<tr>
<th></th>
<th>Geometry 1 (µm)</th>
<th>Geometry 2 (µm)</th>
<th>Geometry 3 (µm)</th>
<th>Geometry 4 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>540° spiral</td>
<td>175/125/75</td>
<td>175/105/55</td>
<td></td>
<td></td>
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<tr>
<td>360° spiral</td>
<td>105/75</td>
<td>105/55</td>
<td></td>
<td></td>
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<tr>
<td>180° spiral</td>
<td>125</td>
<td>105</td>
<td>75</td>
<td>65</td>
</tr>
<tr>
<td>90° spiral</td>
<td>125</td>
<td>105</td>
<td>75</td>
<td>65</td>
</tr>
</tbody>
</table>

The smallest arc segment in each spiral has a diameter well below 100 µm and thus large spacing between its neighboring WG modes, enabling them to function as an effective mode filter in addition to the mode selectivity inherent to the coupled-cavity configuration, which in turn facilitates single-mode operation of the QC lasers. The length of the straight section varies from ~1 mm to ~4 mm and is determined in the facet cleaving process, and the width of the ridges is ~18 µm. The total length and the ridge width of the devices are both similar to typical simple ridge QC lasers.

Lasers with such candy-cane shaped monolithic coupled-cavities are fabricated from QC laser material similar to that used for the hair-pin shaped cavities, with an emission wavelength of ~4.5 µm at cryogenic temperature. The fabrication and packaging processes are also identical to those for the hair-pin shaped cavities described in Section 4.4. Figure 4.18 shows several SEM images of the fabricated devices.
4.7 Characterization results for QC lasers with candy-cane shaped monolithic coupled-cavities

Spectra of a large number of fabricated QC lasers with different candy-cane shaped monolithic coupled-cavity designs and various ridge lengths are characterized with FTIR. The lasers are operated in pulsed-mode with pulse width of 15 ns (to avoid pulse chirping during measurements) and a repetition rate of 80 kHz. The laser spectra show effective suppression of the FP modes associated with the entire cavity length. Single-mode emission (more than 15 dB SMSR) is achieved for all types of spiral structures. For a batch of devices fabricated from the same wafer, a total of 35 devices were tested to estimate the single-mode device yield. Regardless of the geometry details, for devices with 540°, 360°, 180° and 90° spiral structures, the number of single-mode devices versus the number of tested devices are 4 out of 6, 3 out of 5, 4 out of 12 and 3 out of 12, respectively. The relatively higher single-mode device yield for cavity designs with 360° and 540° spirals indicates higher wavelength selectivity associated with such spiral structures. This can be partially attributed to the larger curvature of the inner half-ring section. The output optical power from the front-facet of the single-mode lasers is on the order of a few tens of milliwatt and the maximum observed exceeds 60 mW. We have also explored tapered spiral structures with close to 90° or 180° turns (see Fig 4.19) in attempt to improve the transverse mode selectivity of the spiral structures. QC lasers fabricated
with such tapered spiral structures show similar single-mode performance, and more importantly the single-mode yield is significantly improved compared to the lasers with non-tapered 90° or 180° spirals: 12 out of 18 tested QC lasers with such tapered spiral structures (90° and 180° turns combined) in the laser cavities operate in single-mode, and several of them have a single-mode operating current range of more than 80% of the threshold current. However, they also exhibit slightly higher threshold current density and lower output power, mainly due to the low reflectivity (effectively higher mirror loss) associated with the tapered cavity back-facet.

Fig. 4.19 (a) Schematics the two candy-cane shaped coupled-cavity designs with tapered spiral structures. (b) SEM pictures of two fabricated QC lasers with the candy-cane shaped coupled-cavity designs in (a). (c) Spectrum of a candy-cane shaped coupled-cavity QC laser with a 180° tapered spiral and straight section length of ~1.38 mm, operating in single mode.
Fig. 4.20 Spectra of a candy-cane shaped QC laser with 360° spiral and 1.23 mm straight section length operated at 80 K and at different current values as indicated (threshold current $I_{th}$ ≈ 730 mA).

Figure 4.20 shows the spectra of a laser with a 360° spiral structure (105 μm/75 μm half-ring diameters) and straight section length of ~1.23 mm operated at heat-sink temperature of 80 K. The laser operates in single-mode from the threshold current of ~750 mA up to ~1250 mA (70% above threshold current) with a maximum SMSR of ~25 dB. The single-mode emission wavelength of these candy-cane shaped monolithic coupled-cavity QC lasers can also be tuned by changing the heat-sink temperature. As shown in Fig. 4.21, the emission wavelength of the single-mode QC laser as in Fig 4.20 is continuously, mode-hop free tuned across ~8 cm$^{-1}$ when the heat-sink temperature is changed from 80 K to 155 K.

In addition, current-induced tuning of the laser emission wavelength which is highly desirable for its fast response and accuracy has also been explored and demonstrated with these candy-cane shaped laser cavities. Candy-cane shaped QC lasers with separate metal contacts for the spiral section and the straight section are fabricated. The gap between the metal contacts for the two sections is
30 µm wide as can be seen in Fig. 4.22(a). When such lasers are operated, the straight section is still biased in pulsed mode while the spiral section is biased by a DC current source. The DC current changes the temperature of the spiral structure locally and therefore its modal refractive index, which in turn tunes the mode distribution of the entire coupled-cavity and the emission wavelength. As only the spiral structure is heated by the DC current during tuning, the overall laser performance is relatively well maintained. Figure 4.22(b) shows that the emission wavelength is tuned across ~0.8 cm⁻¹ (mainly limited by the straight section FSR) by changing the DC bias current from 0 mA to 50 mA while keeping the pulsed bias current on the straight section constant. Although rather limited, this tuning range is nevertheless sufficient for many single-species molecular sensing applications. The current tuning process can be much faster than the tuning via the heat-sink temperature, and additional advantages for this separate contact configuration include low DC power consumption and minimal degradation of the laser performance.

![Graph](image-url)

Fig. 4.21 (a) Spectra of the laser in Fig. 4.20 operated at a constant current level (1.05 A) but various heat-sink temperatures. (b) The single-mode emission wavenumber vs. heat sink temperature extracted from the spectra in (a).
Fig. 4.22 (a) SEM image of a candy-cane shaped monolithic coupled-cavity QC laser fabricated with separate metal contacts for the straight section (1.4 mm in length) and the $180^\circ$ spiral section.

(b) Spectra of the laser in (a) operated in pulsed mode (pulsed current through the straight section) above the threshold current at 80 K and with different DC currents through the spiral section.

Fig. 4.23 Single-mode emission wavenumber vs. straight section length for 14 single-mode lasers out of in total 35 tested lasers fabricated from the same wafer.

Similar to the QC lasers with hair-pin shaped cavities, the emission wavelength of the QC lasers with candy-cane shaped cavities can also be shifted across a large range through tailoring the device geometry, e.g. the length of the straight section. Figure 4.23 plots the emission wavenumber versus the straight section length for the 14 single-mode lasers (out of totally 35 tested lasers) with various spiral structures from the same batch of devices. Their emission wavelengths cover a range of
~70 cm$^{-1}$, and a clear trend can be observed that the longer the straight section, the longer the emission wavelength, which is a result of the lower threshold conditions (current density, voltage, electric field) for QC lasers with longer straight sections. The only exception in the plot is likely due to the inhomogeneity of the grown wafer, since that particular QC laser is the only one from the edge of the wafer used.

The performance of these candy-cane shaped lasers is also primarily limited by their high threshold current density which ranges from 2 to 3 times that of simple ridge lasers with similar total length fabricated from the same materials. For instance, the minimum observed threshold current density for single-mode lasers with ~2.6 mm total length is ~1.5 kA/cm$^2$ compared to ~0.6 kA/cm$^2$ for simple ridge lasers, while for total length of ~1.4 mm the comparison is ~2.3 kA/cm$^2$ versus ~1.3 kA/cm$^2$. Such high threshold current density impedes high temperature or CW operation of the devices. The major cause for the high threshold current density, similar to that of the hair-pin shaped lasers, is due to the transverse mode coupling loss between the straight section and the spiral section. However, the threshold current density for the candy-cane shaped lasers is significantly lower than that of the hair-pin shaped lasers of similar total cavity length. This reduced threshold current density is mainly attributed to the lower mode coupling loss since only one interface instead of two between the straight section and the curved section is present in a candy-cane shaped cavity.

This issue is further studied with a simple model as described below which quantitatively relates the high threshold current density to the transverse mode coupling loss at the geometrical boundaries between the straight sections and the spiral sections. Taking a candy-cane shaped cavity with 180° spiral structure as an example, the laser threshold current density approximately satisfies the following equation derived from the requirement that at threshold light propagating a round trip in the laser cavity experiences zero net gain (loss):

$$e^{(g/\Gamma_{TH} - \alpha) \times 2L} \times C_{ij}^2 \times e^{(g/\Gamma_{TH} - \alpha) \times 2S} \times R_f R_b = 1 ,$$  \hspace{1cm} (4.5)
where $g$ is the gain coefficient, $J_{TH}$ is the threshold current density, $\Gamma$ is the mode confinement factor, $C_{i,j}$ is the coupling coefficient between the $i_{th}$ transverse mode in the straight section (the corresponding waveguide loss is $\alpha$) and the $j_{th}$ transverse mode in the spiral section which is a half-ring in this case (the corresponding waveguide loss is $\alpha'$), $L$ is the length of the straight section and $S$ is the perimeter of the spiral, $R_f$ and $R_b$ are the mirror reflectivities for the front-facet and the back-facet (the end of the spiral), respectively. Reflection of light at the geometrical boundary between the two sections is relatively weak and therefore neglected in this equation. In the half-ring section, the intensity profiles of the transverse modes (radial modes of the WG modes) have peaks localized close to the outer side-wall (Fig. 4.24), while the intensity profiles of the transverse modes in the straight section are mirror symmetric [39], therefore the coupling coefficient $C_{i,j}$ is significantly lower than unity and its contribution to the threshold current density is expected to be comparable or even larger than the mirror loss of an as-cleaved facet. By the same token, the coupling coefficient associated with the first order transverse mode in the straight section and a certain transverse mode in the spiral is expected to be higher than those for the fundamental mode or other higher order modes in the straight section because of their larger spatial overlap, therefore the lasers should have the tendency to lase in the first order transverse mode in the straight section. In fact, this is observed in the laser far-field characterizations resolved for individual lasing modes. The schematic of the setup for such characterizations is illustrated in Fig. 4.25. Some examples of the measurement results are given in Fig. 4.26. For all the lasers characterized (single-mode or not), most of the lasing modes show a double-peak far-field pattern (e.g. Fig. 4.26(a)), while single-peak (e.g. Fig. 4.26(b)) and triple-peak (e.g. Fig. 4.26(c)) far-field patterns occur rarely.
Fig. 4.24 Simulation results of the WG modes with the lowest three orders in the radial direction associated with a quarter-ring waveguide which has ~50 \( \mu \text{m} \) radius and 18 \( \mu \text{m} \) ridge width.

Fig. 4.25 Schematic of the characterization setup for laser far-field resolved for individual lasing modes. The laser beam is collimated with a ZnSe lens and sent into the FTIR through a movable slit. The spectrally resolved far-field profile is obtained from the intensity of individual modes vs. the slit position.
Fig. 4.26 Far-field measurements for individual lasing modes of three different candy-cane shaped monolithic coupled-cavity QC lasers which exhibit (a) double-peak, (b) single-peak, and (c) triple-peak far-field patterns, respectively. The spectra of the lasing modes (highlighted with red circles) corresponding to the far-field patterns are shown in the inset of the diagrams.
Additionally, for the candy-cane shaped monolithic coupled-cavities, contributions to the high threshold current density also include the low mirror reflectivity from the wet-etched (instead of as-cleaved) back-facet, the bending loss introduced by the high-curvature spiral section and the relatively higher waveguide loss associated with the aforementioned transverse modes which interact more with the side-wall metal contact. In order to increase the reflectivity of the back-facet and further decrease the threshold current density, approaches such as post-fabrication of a high-quality back-facet with focused ion beam milling can be applied, however, at the same time it would more or less compromise the fabrication simplicity of such monolithic coupled-cavities. Further optimization of the cavity structures assisted by comprehensive modeling to improve the transverse mode coupling is expected to be a more promising way to considerably reduce the threshold current density.

4.8 Conclusions and discussions

In this project we have first proposed and then demonstrated that monolithic structures consisting of a straight waveguide connected with a curved waveguide with large curvature can function as the building block for a novel class of coupled-cavities, because reflection of light takes place at the geometrical boundary between the straight waveguide and the curved waveguide thanks to the spatial mismatch and different modal refractive indices of the transverse modes associated with the two different sections. Although such light reflection may be relative weak, it still provides significant wavelength selectivity in a coupled-cavity configuration according to our theoretical analysis on coupled-cavities.

Applying this idea and extensively making use of the generic building block, we have implemented a number of different monolithic coupled-cavity designs with different shapes and varying geometry details, which include the hair-pin shaped cavities and the candy-cane shaped cavities. The curved sections in these two types of monolithic coupled-cavities have bending radii well below 100 µm, and therefore function as highly selective mode filters in the coupled-cavities.
The major role of the straight sections is to provide sufficient optical gain and to allow for efficient out-coupling of the light. The key technological advantage for such monolithic coupled-cavity structures is that their fabrication processes are identical to those for simple ridge lasers, and therefore they are a promising solution to achieving cost-effective single-mode QC lasers.

Single-mode operation of QC lasers employing such monolithic coupled-cavities is indeed achieved with high SMSR (up to 27 dB) and large single-mode operating current range (up to more than 70% of the threshold current). All the designed hair-pin shaped cavities and candy-cane shaped cavities are capable of facilitating single-mode operation, however, from the large number of devices characterized it is observed that cavities with higher curvature sections allow for a higher single-mode device yield, which is also in agreement with the theoretical analysis of the wavelength selectivity for such coupled-cavity structures. Furthermore, the single-mode emission wavelength has been demonstrated to be continuously, mode-hop free tunable by either changing the operating temperature or changing the DC bias current through part of the device such as the compact curved section, and the typical wavelength tuning range (several wavenumbers) is sufficient for many absorption spectroscopy based trace gas sensing applications. On the other hand, the emission wavelength can also be controllably shifted over a much wider range (over 70 cm\(^{-1}\) for a ~4.5 µm QC material) by tailoring the device geometry such as the straight section length, which changes the laser threshold conditions and therefore the emission wavelength. Combined with the wavelength tunability, such a wavelength shifting mechanism compatible with the monolithic coupled-cavities offers the flexibility to hit absorption lines of multiple target molecules with the same batch of fabricated devices (provided the absorption lines of interest are not separated too far apart), which is not possible for single-mode QC lasers employing single integrated periodic feedback structures.
Fig. 4.27 Modified hair-pin shaped coupled-cavities with (a) the outer radius of the half-ring section made smaller and (b) the inner radius of the half-ring section made larger, in order to improve the spatial overlap between transverse mode in the straight sections and the half-ring section.

For the demonstrated monolithic coupled-cavity structures, however, one common major drawback is that the transverse mode coupling loss between the straight and the curved sections is quite large and has a significant contribution to the observed high laser threshold current density, which is the major factor limiting the overall device performance. The bending loss and higher waveguide loss associated with the large-curvature curved waveguides also contribute to the high threshold current density but probably in a much less dominant fashion. We expect that the transverse mode coupling loss (it is estimated to be $\sim 8 \text{ cm}^{-1}$ from the laser threshold increase) can be greatly reduced with carefully optimized cavity structures which would be the core of future effort on advancing this field. We have experimented with a few modified hair-pin shaped cavities (Fig. 4.27) aiming to improve the mode coupling by increasing the spatial overlap between the transverse modes in the different sections. However, they have not shown any significant improvement yet.

The demonstrated coupled-cavities are mostly designed with guidance of educated guesswork as well as trial and error. A comprehensive model which would provide accurate prediction of the mode distributions for such cavity structures is needed for accomplishing the challenging but rewarding task of achieving high-performance cost-effective single-mode QC lasers with such monolithic coupled-cavities. Such modeling work is beyond the scope of this thesis and may be the focus of future theoretical work.
References


Chapter 5

Single-mode Quantum Cascade Lasers Employing Asymmetric Mach-Zehnder Interferometer Type Cavities

5.1 Motivation

The monolithic coupled-cavity designs described in the previous chapter not only prove to be a cost-effective solution to achieving tunable single-mode QC lasers, but also introduce a new cavity design concept, i.e., facilitating single-mode operation of QC lasers by monolithically integrating a wavelength selective structure into a simple ridge FP cavity which is an ideal structure for providing optical gain. Such a cavity design concept can be further extended to combine with other “tools” in the “toolbox” to forge new cost-effective single-mode QC laser solutions which would also incorporate the advantages of the specific tools. A good candidate of such tools is the Mach-Zehnder (MZ) interferometer which has been employed in various fields and in different forms due to its powerful ability to exploit and manipulate the phase information of the concerned waveforms, e.g., MZ interferometers have been used in studying the quantum coherence of entangled photons [1] and electrons [2]; they have also been applied to microscopy [3, 4], spectroscopy [5, 6] as well as interferometric sensing technologies [7, 8]; moreover, in fiber-optic communication networks, MZ interferometers are frequently used as power modulators [9], wavelength converters [10], switches [11] and multiplexers/demultiplexers [12, 13], filters [14], etc. An obvious advantage of MZ interferometer structures is that they are relatively easy to fabricate with high throughput and yield, similar to ridge waveguide structures. Another crucial advantage for MZ interferometers is that with proper designs, they can be coupled to straight waveguide structures such as a simple ridge laser with low coupling loss, and therefore introduce minimal device performance degradation when
monolithically integrated into a simple ridge FP cavity as a wavelength selective unit to facilitate single-mode operation. However, for such a purpose the MZ interferometers must be designed to be asymmetric, i.e., the two interferometer arms have different lengths, in order to introduce sufficient wavelength selectivity in the cavity. Symmetric MZ interferometers have previously been applied to QC lasers for different purposes, e.g., for interferometric sensing of chemicals and power modulation [15] or for coherent power combining [16]; however, no significant reduction in the number of laser modes were observed due to the lack of wavelength selectivity of symmetric MZ interferometers. In contrast, asymmetric Mach-Zehnder (AMZ) interferometers can have strong and design-controllable wavelength selectivity.

5.2 Wavelength selectivity of AMZ interferometers and cavity design considerations

A typical top-view schematic of such a proposed AMZ interferometer type laser cavity is shown in Fig. 5.1(a). The entire cavity consists of two straight waveguides sandwiching an AMZ interferometer whose two arms have a length difference $\Delta L$. A lightwave of a specific frequency (with wavenumber $k_m$) entering one end of the AMZ interferometer is split into the two arms equally by the symmetric Y-splitter structure. If the coherence length of the light is much longer than the interferometer arms, then the two lightwaves traveling through the two different interferometer arms recombine through the Y-splitter (combiner) at the other end of the interferometer with a relative phase difference $\Delta \varphi = 2\pi n_{\text{eff}} k_m \Delta L$, where $n_{\text{eff}}$ is the effective refractive index of the waveguide. If $\Delta \varphi = 2N\pi$ where $N$ is an integer, the lightwaves from the two arms interfere constructively along the central axis of the Y-splitter stem, corresponding to the maximum transmission through the interferometer structure; on the contrary, if $\Delta \varphi = (2N + 1)\pi$, the lightwaves interfere destructively along the center of the Y-splitter stem but constructively closer to the side walls, which corresponds to a high-loss scenario and hence the minimum transmission. Thus, the transmission spectrum of the AMZ interferometer is a periodic function with a period in terms of wavenumber
\[ \Delta k = 1/n_{\text{eff}} \Delta L , \]  

(5.1)

and if considering only the fundamental transverse mode and neglecting the waveguide loss, the transmission spectrum can be approximated as

\[ T(k) = \cos^2\left(\pi n_{\text{eff}} \cdot \Delta L \cdot k \right). \]  

(5.2)

With cleaved facets functioning as mirrors on each end of the cavity in Fig. 5.1(a), the cavity essentially behaves as a FP cavity with well defined FSR. When a lightwave with wavenumber \( k \) enters the AMZ interferometer and gets split into the two arms equally, the wave traveling across the shorter arm picks up a phase change of \( \pi n_{\text{eff}} k L_1 \) and the wave traveling across the longer arm picks up a phase change of \( \pi n_{\text{eff}} k L_2 \). When the two waves recombine at the other end of the AMZ interferometer and coherently interfere with each other, their superposition then has a phase change of \( \pi n_{\text{eff}} k (L_1 + L_2)/2 \), therefore the effective length of the AMZ interferometer is the average length of the two interferometer arms \( (L_1 + L_2)/2 \), and we denote it with \( L_{\text{avg}} \). In this way, the FSR of the FP modes associated with an AMZ interferometer type cavity is derived to be

\[ \text{FSR} = 1/2 n_{\text{eff}} (L_R + L_{\text{avg}}) , \]  

(5.3)

where \( L_R \) is the total length of the straight waveguides on both sides of the AMZ interferometer. As is illustrated in Fig. 5.1(b), the lasing modes for such an AMZ interferometer type cavity are selected by three factors: the optical gain profile, the FP modes of the cavity and the transmission spectrum of the AMZ interferometer. If the distance between neighboring transmission peaks of the AMZ interferometer is large enough so that the optical gain discrimination between neighboring transmission peaks (\( \delta_1 \) in Fig. 5.1(b)) is sufficient, only one group of FP modes within the transmission peak closest to the optical gain spectrum peak would lase. If at the same time the transmission peak is narrow enough so that the transmission loss discrimination between neighboring FP modes within this transmission peak (\( \delta_2 \) in Fig. 5.1(b)) is sufficient, then only the mode with the highest transmission would lase, leading to single-mode operation. In fact, such wavelength selectivity of AMZ interferometers has been exploited in various applications including lasers. It was

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first introduced in gas lasers [17] and later extensively applied to fiber-based lasers [18-20], however, its application in semiconductor lasers has so far been rather limited [21-23].

Fig. 5.1 (a) Schematic of a typical AMZ interferometer type laser cavity design and magnified drawing of the Y-splitter section. (b) Schematic of the laser mode selection mechanism in QC lasers with AMZ interferometer type cavities. The shaded area highlights representative lasing FP modes which are located at the peak optical gain and a transmission peak of the AMZ interferometer structure.

As the narrowness of the transmission peaks and the distance between neighboring peaks change oppositely with respect to $\Delta L$, there is an optimal range of $\Delta L$ for facilitating single-mode operation. When $\Delta L$ assumes the optimum value, the optical gain discrimination $\delta_1$ should equal the transmission loss discrimination $\delta_2$, corresponding to the largest overall net gain discrimination between the dominant mode and any other modes. A rough estimation of this optimum value of $\Delta L$ is performed based on the aforementioned model of the AMZ interferometer transmission and the cavity FSR described through Eqns. (5.1) to (5.3). Assuming the optical gain has the Lorentzian lineshape

$$g(k) = g_0 \frac{(\gamma/2)^2}{(k-k_0)^2 + (\gamma/2)^2},$$

(5.4)
where \( g_0 \) is the peak optical gain at the transition energy \( k_0 \) (in terms of wavenumber) and \( \gamma \) is the full width at half maximum (FWHM) of the optical gain spectrum, and that a particular transmission peak of the AMZ interferometer coincides with the optical gain spectrum peak, then the optical gain discrimination \( \delta_1 \) associated with its neighboring transmission peaks is

\[
\delta_1 = g_0 \left( 1 - \frac{(\gamma/2)^2}{\Delta k^2 + (\gamma/2)^2} \right).
\]  
(5.5)

where \( \Delta k \) is given by Eqn. (5.1). If a FP mode is positioned exactly at this particular transmission peak, the transmission loss discrimination \( \delta_2 \) associated with its neighboring FP modes is given as

\[
\delta_2 = \frac{-\ln(\cos^2(\pi n_{eff} \cdot \text{FSR} \cdot \Delta L))}{L_{avg}}.
\]  
(5.6)

For QC lasers with emission wavelength around 5 to 7 \( \mu \)m range (the QC laser materials we employed for this project have emission wavelengths within this range), \( \gamma \) has a typical value of \(~200 \text{ cm}^{-1}\), and at the laser threshold the peak modal gain \( g_0 \) which is equal to the total loss has a typical value of 10 \text{ cm}^{-1} (~4 \text{ cm}^{-1} \text{ mirror loss and} \sim 6 \text{ cm}^{-1} \text{ waveguide loss}), if the total cavity length \( L_R + L_{avg} \) maintains the typical value of \(~3 \text{ mm} \) which also determines the FSR to be \(~0.5 \text{ cm}^{-1} \). For AMZ interferometer designs with aforementioned low loss Y-splitters, practical values for \( L_{avg} \) is \(~2 \text{ mm} \) though can be moderately reduced with further optimization. Based on the above parameters, the optimum value of \( \Delta L \) is estimated by equating \( \delta_1 \) and \( \delta_2 \) in Eqns. (5.5) and (5.6) to be \(~300 \mu m \) (Fig. 5.2). However, this value is likely an underestimate since the narrowness of the transmission peaks described by the idealized Eqn. (5.2) and as a consequence \( \delta_2 \) described by Eqn. (5.6) are overestimated. If for example assuming the AMZ interferometer transmission spectrum has a lower contrast between peaks and valleys than that described by Eqn. (5.2) and is instead described by

\[
T(k) = \frac{\cos^2(\pi n_{eff} \cdot \Delta L \cdot k)}{X} + \frac{X-1}{X},
\]  
(5.7)

where the contrast is \( 1/X \), then the estimation of the optimum value of \( \Delta L \) for \( X = 2 \) would be \(~360 \mu m \) (Fig. 5.2). Nevertheless, these estimations can be treated as design guidance, and the actual optimal range of \( \Delta L \) still needs to be explored experimentally. On the other hand, Eqns. (5.3) and (5.6)
suggest that $L_{avg}$ is also a critical design parameter that the AMZ interferometers should be as compact as possible to minimize the FSR of the FP modes and maximize the transmission loss discrimination $\delta_2$. Furthermore, the cavity ridge width should be small enough to suppress higher order waveguide transverse modes.

![Graph showing calculations of gain discrimination (blue curve) and loss discriminations (red curves) with AMZ interferometer type cavity](image)

Fig. 5.2 Calculations of the gain discrimination (blue curve) and the loss discriminations (red curves) that can be achieved with an AMZ interferometer type cavity with design parameter $\Delta L$. The assumed FWHW of the optical gain spectrum is 200 cm$^{-1}$. The solid red curve is based on the transmission spectrum of the AMZ interferometer given in Eqn. (5.2) while the dashed red curve on that given in Eqn. (5.7) with $X = 2$.

### 5.3 First generation designs of AMZ interferometer type cavities for mid-IR QC lasers

In order to fully explore the design parameter space, a number of AMZ interferometer type cavities with different shapes and $\Delta L$ values varying from 50 $\mu$m to 400 $\mu$m are designed and compose the first generation cavity designs, the schematics of which are shown in Fig. 5.3(a) as Designs I to IV. The symmetric Y-splitter structures in all the designs have splitting branches with
sufficiently large bending radius of 300 µm (see Fig. 5.1(a) for the detailed drawing) to allow for adiabatic transitions and thus minimize the coupling loss at the junctions between the AMZ interferometer and the straight waveguides. All the other curved sections in both interferometer arms are also symmetric, therefore \( \Delta L \) originates from the difference between the straight sections in each interferometer arm.

![Figure 5.3](image)

Fig. 5.3 (a) Detailed schematics of several first generation AMZ interferometer type QC laser cavity designs. (b) Optical microscope images of several fabricated devices with the corresponding cavity designs shown in (a).

Four different AMZ interferometers are based on Design I (30° turning angle for all the curved sections) but with different straight section lengths and thus \( \Delta L \) takes values of 50 µm, 65 µm, 100 µm and 150 µm, respectively, and the average length of the interferometer arms \( L_{\text{avg}} \) takes values of \(~1.2\) mm, \(~1.3\) mm, \(~1.5\) mm and \(~1.8\) mm, respectively. For Designs II to IV, the turning angles
of the curved sections are increased gradually (45° for Design II, 60° for Design III and 90° for Design IV, respectively) which allows for the realization of larger $\Delta L$ with even smaller $L_{\text{avg}}$, an additional benefit to the wavelength selectivity. In order to avoid excessive lateral dimension, instead of a constant 300 $\mu$m bending radius like those in Designs I and II, the curved sections in Design III and IV consist of arcs with different radii: a 30° arc with 300 $\mu$m radius connecting to a 30° arc with 150 $\mu$m radius in Design III and a 30° arc with 300 $\mu$m radius connecting to a 60° arc with 100 $\mu$m radius in Design IV, respectively. However, the downside of such curved sections is that extra coupling loss and bend loss are introduced. One interferometer is designed based on each of Designs II to IV, in which $\Delta L$ takes values of 200 $\mu$m, 300 $\mu$m and 400 $\mu$m, respectively, while $L_{\text{avg}}$ takes values of $\sim$1.6 mm, $\sim$1.5 mm and $\sim$1.5 mm, respectively. The design parameters for all the first generation AMZ interferometer type cavities are summarized in Table 5.1.

QC lasers with the first generation AMZ interferometer type cavities are fabricated from a QC laser material based on an ultra-strong coupling design (wafer No. A1392) with an emission wavelength around 6.5 $\mu$m and extremely broad optical gain spectra (FWHM of $\sim$484 cm$^{-1}$ at 80 K and $\sim$662 cm$^{-1}$ at 300 K). The cavity structures are patterned by photolithography and wet etched through the epitaxial layer with $\sim$10 $\mu$m in height and the ridge width is $\sim$9 $\mu$m; SiO$_2$ ($\sim$3500 Å) is deposited using plasma-enhanced chemical vapor deposition for electrical insulation; contact windows on top of the entire cavity are opened using reactive-ion etching; top Ti/Au ($\sim$200/1500 Å) metal contact is deposited with electron-beam evaporation from three different angles (0°, +45°, -45°) to ensure uniform coverage over the deep-etched ridges; the substrate is thinned to $\sim$200 $\mu$m and bottom Ge/Au ($\sim$300/2000 Å) metal contact is deposited with electron-beam evaporation. Devices from all different designs are cleaved to form the laser facets as well as to define the total length of the cavities, and then mounted epitaxial-side-up to copper heat sinks. Fig. 5.3(b) shows the optical microscope images of several fabricated devices corresponding to the design schematics in Fig. 5.3(a).
Table 5.1 Design details of the first generation AMZ interferometer type cavities

<table>
<thead>
<tr>
<th>Interferometer No.</th>
<th>Design No.</th>
<th>∆L (μm)</th>
<th>L_{avg} (mm)</th>
<th>Length (mm)</th>
<th>Width (μm)</th>
<th>Curved section turning angles (°)</th>
<th>Curved section radii (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferometer 1</td>
<td>I</td>
<td>50</td>
<td>1.18</td>
<td>1.11</td>
<td>341</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>Interferometer 2</td>
<td>I</td>
<td>65</td>
<td>1.28</td>
<td>1.20</td>
<td>370</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>Interferometer 3</td>
<td>I</td>
<td>100</td>
<td>1.46</td>
<td>1.37</td>
<td>411</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>Interferometer 4</td>
<td>I</td>
<td>150</td>
<td>1.78</td>
<td>1.67</td>
<td>504</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>Interferometer 5</td>
<td>II</td>
<td>200</td>
<td>1.63</td>
<td>1.42</td>
<td>665</td>
<td>45</td>
<td>300</td>
</tr>
<tr>
<td>Interferometer 6</td>
<td>III</td>
<td>300</td>
<td>1.50</td>
<td>1.20</td>
<td>729</td>
<td>30/30</td>
<td>300/150</td>
</tr>
<tr>
<td>Interferometer 7</td>
<td>IV</td>
<td>400</td>
<td>1.50</td>
<td>1.00</td>
<td>822</td>
<td>30/60</td>
<td>300/100</td>
</tr>
</tbody>
</table>

5.4 Characterizations of QC lasers with the first generation AMZ interferometer type cavity designs

QC Lasers with the first generation cavity designs and a range of total lengths are extensively characterized at various heat-sink temperatures in pulsed mode and a significant fraction also in CW mode. The laser spectra are measured with a FTIR and the LIV characteristics are taken in the standard LIV setup (see Appendix A).

A significant reduction in the number of lasing modes is observed in the spectra of all the QC lasers with any AMZ interferometer cavity design compared to that of a simple ridge FP cavity QC laser fabricated from the same material. Figure 5.4 shows such comparisons: the spectra of the FP cavity QC laser operated in pulsed mode at 80 K contain more than 30 dominant lasing modes (Fig. 5.4(a)), however, for the AMZ interferometer type cavities with even the smallest ∆L values (50 μm and 65 μm), the number of dominant lasing modes is dramatically reduced to below 10 under similar operating conditions and all of the lasing modes are within one transmission peak of the AMZ interferometer (Fig. 5.4(b)-(d)). Other interesting observations include that if we compare QC lasers with similar total cavity length but different ∆L values (50 μm in Fig. 5.4(b) vs. 65 μm in Fig. 5.4(d)),
the laser with larger $\Delta L$ has fewer lasing modes which can be attributed to the narrower transmission peaks associated with the AMZ interferometer with larger $\Delta L$; on the other hand if we compare QC lasers with the same AMZ interferometer design and hence same $\Delta L$ but different total cavity lengths (3.1 mm in Fig. 5.4(c) vs. 2.4 $\mu$m in Fig. 5.4(d)), the shorter device has fewer lasing modes which is due to a larger FSR of the cavity FP modes. Such observations agree well with our previous analysis on the mode selection mechanism of the AMZ interferometer type cavities in Section 5.2, and are consistently further verified by the spectral features of QC lasers with even larger $\Delta L$ values in the cavity designs.

Fig. 5.4 (a) Spectra of a FP cavity (simple ridge) laser at different operating current densities. (b)-(d) Spectra of 3 QC lasers with different AMZ interferometer type cavity designs and/or cavity lengths at different operating current densities. The cavity design parameters are specified in the diagrams. All the spectra are taken at 80 K in pulsed operation.
Fig. 5.5 Spectra of 4 QC lasers with different AMZ interferometer type cavity designs and/or cavity lengths operated moderately above the laser threshold current at 80 K in pulsed mode.

Figure 5.5 shows the exemplary spectra of QC lasers with increasing ∆L values (100 µm, 150 µm, 200 µm and 300 µm, respectively) in the cavity designs operated in pulsed mode at 80 K. It is clear that the numbers of lasing modes are further reduced with these cavities, and the larger the ∆L of the AMZ interferometer is, the fewer neighboring FP modes (within one transmission peak of the AMZ interferometer) are observed, and two-mode operation is achieved consistently for the tested QC lasers with cavities of Design III (∆L = 300 µm). More importantly, for all the spectra of the QC lasers with different AMZ interferometer type cavities shown in Fig. 5.4 and Fig. 5.5, the separations between neighboring FP modes also accurately match the prediction of the FSR given by Eqn. (5.3), and this is a strong evidence that the lightwaves from the two arms of the AMZ interferometer are coherently coupled to and interfere with each other after being combined by the Y-splitters.

Extending the parameter ∆L a little bit further to 400 µm (Design IV), single-mode operation of QC lasers is achieved reliably across different devices in pulsed mode operation. This suggests that a ∆L of around 400 µm is a favored region in the design parameter space for facilitating single-mode operation, which agrees well with our previous theoretical estimation of the optimum value for ∆L.
Fig. 5.6 (a) Spectra of a single-mode QC laser with AMZ interferometer type cavity ($\Delta L = 400 \ \mu m$) operated at various current densities at 80 K in pulsed mode. (b) Spectra in (a) plotted in the log scale.

Fig. 5.7 (a) Spectrum of the same laser in Fig. 5.6 operated at 200 K in pulsed mode. (b) Spectrum of a QC laser with AMZ interferometer type cavity ($\Delta L = 300 \ \mu m$) operated far above the threshold current at 80 K in pulsed mode.
Figure 5.6 shows the spectra of such a QC laser with total cavity length of ~1.9 mm operated in pulsed mode at 80 K with SMSR up to 20 dB. The single-mode operating current range in pulsed mode at 80 K for the characterized devices is typically within 700 mA to 800 mA, approximately to twice the threshold current. When operated at even higher pump current or at much higher temperatures which broadens and also shifts the optical gain spectrum, either additional neighboring FP modes or additional groups of lasing modes appear in the spectra. For QC lasers with other cavity designs which have a few FP modes within one AMZ interferometer transmission peak when operated moderately above the laser threshold current, multiple groups of lasing modes also emerge at much higher pump current. When multiple groups of lasing modes are present in the laser spectrum, e.g. the spectra in Fig. 5.7, they are usually separated from each other with equal distance that matches very well the periodicity of the AMZ interferometer transmission peaks described in Eqn. (5.1). This further confirms that our model of the AMZ interferometer type cavities, though being analytical and relatively simple, offers satisfactory accuracy on predicting the cavity wavelength selectivity and mode distributions.

Pulsed LIV characteristics of the single-mode QC lasers are also measured and compared to that of simple ridge QC lasers from the same material and with similar total cavity lengths, and an example is given in Fig. 5.8. It can be seen that the threshold current density of the single-mode QC laser with AMZ interferometer type cavity ($\Delta L = 400 \mu m$) is significantly higher than that of a simple ridge FP cavity QC laser, which is mainly due to the coupling loss between the straight waveguide sections and the Y-splitters as well as the coupling loss between curved sections of different curvatures, while for lasers with other AMZ interferometer cavities in which the curved sections have constant 300-µm radius, the threshold current density is significantly lower. The slope efficiency and maximum output optical power are also affected and significantly lower than those of the FP cavity lasers. Nevertheless, it is worth pointing out that the overall performance of the single-mode QC
lasers employing the first generation AMZ interferometer type cavities is in general better than that of the single-mode QC lasers employing monolithic coupled-cavities described in the previous chapter.

Fig. 5.8 (a) Pulsed LIV characteristic of a QC laser with AMZ interferometer type cavity ($\Delta L = 400 \, \mu m$) and cavity length of ~1.7 mm operated at 80 K. (b) Pulsed LIV characteristic of a FP cavity QC laser with cavity length of ~1.7 mm operated at 80 K.

The above characterization results for the first generation devices have proved that the proposed AMZ interferometer type cavity design concept is viable for achieving single-mode operation of QC lasers, and also provide us with clear guidelines on how to further optimize the cavity designs: (1) the sweet-spot in the design parameter space for $\Delta L$ is found to be around 400µm (although the value is likely dependent on the wavelength and the optical gain spectrum profile),
therefore further cavity design optimizations should be based on such a reference value for \( \Delta L \); (2) the average length of the interferometer arms \( L_{\text{avg}} \) should be further decreased to enhance the wavelength selectivity and increase the FSR associated with the cavities; (3) in order to further reduce the coupling loss and bend loss, curved waveguide structures with non-constant and/or large curvatures should be avoided in improved cavity designs. In fact, there is plenty of room to further improve the cavity designs following the above aspects.

5.5 Second generation designs of AMZ interferometer type cavities with improved wavelength selectivity

Following the guidelines for the optimization of the AMZ interferometer type cavities, 4 new cavity designs (Designs V to VIII) with significant changes in the AMZ interferometers are implemented. The schematics of these second generation designs are illustrated in Fig. 5.9(a). The most distinctive and crucial change applied to these second generation designs is that the curved waveguide sections in the two arms of the interferometers are designed to be unbalanced, meaning that they do not have equal turning angles. In this way, the difference between the curved sections in the two interferometer arms readily introduce a considerably large path length difference required for the wavelength selectivity, therefore the length of the straight waveguide sections in both interferometer arms (which is solely responsible for introducing the desired path length difference \( \Delta L \) in the first generation designs) can be significantly reduced. As a result, the length of each interferometer arm as well as their average length \( L_{\text{avg}} \) are also substantially reduced and the wavelength selectivity (see Eqn. (5.6)) and the FSR associated with a given cavity (see Eqn. (5.3)) are both increased. The reduction in the length of each interferometer arm also leads to the shrinkage of the overall physical dimensions of the entire AMZ interferometer, which not only reduces the device footprint and thus lowers the cost, but also allows for applying curved waveguide structures with large and constant radius and therefore minimizes the coupling loss and the bend loss. For all the
second generation AMZ interferometer designs, the bending radius for all the curved sections is again set to be 300 µm, which proves to work well in the first generation designs.

Fig. 5.9 (a) Detailed schematics of the second generation AMZ interferometer type QC laser cavity designs. (b) Optical microscope images of several fabricated devices with the corresponding cavity designs shown in (a).

<table>
<thead>
<tr>
<th>Design No.</th>
<th>ΔL (µm)</th>
<th>Lavg (mm)</th>
<th>Length (mm)</th>
<th>Width (µm)</th>
<th>Curved section turning angles (°)</th>
<th>Curved section radii (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferometer 1</td>
<td>V</td>
<td>350</td>
<td>1.43</td>
<td>1.21</td>
<td>576</td>
<td>30/60</td>
</tr>
<tr>
<td>Interferometer 2</td>
<td>VI</td>
<td>400</td>
<td>1.42</td>
<td>1.18</td>
<td>594</td>
<td>30/70</td>
</tr>
<tr>
<td>Interferometer 3</td>
<td>VII</td>
<td>450</td>
<td>1.45</td>
<td>1.19</td>
<td>622</td>
<td>30/75</td>
</tr>
<tr>
<td>Interferometer 4</td>
<td>VIII</td>
<td>500</td>
<td>1.48</td>
<td>1.19</td>
<td>650</td>
<td>30/80</td>
</tr>
</tbody>
</table>
Since among all the first generation AMZ interferometer designs, the one with $\Delta L$ of 400 $\mu$m (but not the one with $\Delta L$ of 300 $\mu$m) is found to be capable of introducing sufficient wavelength selectivity and facilitating single-mode operation of the QC lasers with an extremely broad optical gain spectrum, and this value of $\Delta L$ also matches quite well the previous theoretical estimation of the optimum range for $\Delta L$, the values of $\Delta L$ for the second generation designs are chosen to be around 400 $\mu$m, specifically, the 4 different AMZ interferometer designs employ $\Delta L$ of 350 $\mu$m, 400 $\mu$m, 450 $\mu$m and 500 $\mu$m, respectively, corresponding to Designs V to VIII in Fig. 5.9(a). These relatively large $\Delta L$ values are achieved mainly with the unbalanced curved sections in the two arms. In one arm of all the AMZ interferometers, each curved section has a turning angle of 30˚; in the other arm, each curved section has a substantially larger turning angle which is designed to be 60˚, 70˚, 75˚ and 80˚ in Designs V to VIII, respectively. Compared with the interferometers with similarly large $\Delta L$ from the first generation, these second generation designs have even larger $\Delta L$ and reduced $L_{avg}$ without need for reducing the bending radius of the curved sections. The details of Designs V to VIII are summarized in Table 5.2. It is also worth noting that although the curved sections in the two arms of each second generation interferometer design have much different lengths, it is assumed that the Y-splitter structures nonetheless split the incoming lightwave into the two arms approximately equally since it is still a symmetric structure within the first 30˚ arc of both splitting branches. Such an assumption can be tested by measuring the FSR of the cavity FP modes when the spectra of the QC lasers employing the second generation cavity designs show multiple neighboring FP modes at certain operating conditions, because if the power of the lightwaves traveling in the two interferometer arms are far from balanced, then Eqn. (5.3) would not be accurate in describing the FSR.

QC lasers with the second generation AMZ interferometer type cavities are realized from a different QC laser material based on an ultra-strong coupling design (wafer No. A1641) with an emission wavelength around 5.0 $\mu$m and a narrower optical gain spectra (FWHM of $\sim$230 cm$^{-1}$ at 80 K and $\sim$470 cm$^{-1}$ at 300 K) compared to that used for the first generation cavity designs, aimed for
achieving improved high temperature single-mode performance with the second generation lasers. Although not as broad as that of the ~6.5 µm QC laser material, the optical gain spectrum for the newly chosen QC laser material is still wider than most conventional designs around the similar wavelength range. The device fabrication and packaging follows the identical processes for the first generation. The optical microscope images of 4 fabricated QC lasers with corresponding cavity designs in Fig. 5.9(a) are shown in Fig. 5.9(b).

5.6 Characterizations of QC lasers with the second generation AMZ interferometer type cavity designs

QC lasers with all the second generation AMZ interferometer type cavity designs and various total cavity lengths are extensively characterized, and single-mode operation in both pulsed and CW modes is achieved with all four designs. When the QC lasers are driven in pulsed mode, single-mode operation is achieved at various heat-sink temperatures from 80 K up to 300 K with SMSR up to ~20 dB, although the emission wavelength is not tuned continuously, mode-hop free over the entire temperature range and occasionally additional FP modes appear in the laser spectrum at certain temperatures.

Figure 5.10 shows the spectra of an exemplary QC laser with ∆L = 450 µm in its AMZ interferometer structure operating in single-mode at various heat-sink temperatures. Compared to the performance of the first generation QC lasers with AMZ interferometer type cavities which exhibit single-mode operation only at temperatures below 200 K, the significant improvement in the single-mode operation temperature (up to at least 300 K) with these second generation QC lasers is partly attributed to the improved wavelength selectivity of the AMZ interferometer designs, and partly due to the narrower optical gain spectrum of the QC laser material used here. As the operating temperature changes, the optical gain spectrum redshifts as well as broadens, the transmission peaks associated with the AMZ interferometer also redshift due to the increase of the waveguide effective refractive index with temperature (the temperature coefficient dn/dT of the effective refractive index
is on the order of $10^{-4}$ K$^{-1}$ [24]), however, since the redshifts of the optical gain spectrum and the transmission peaks have different rates, mode-hops and additional lasing modes occur when tuning of the operating temperatures across more than 200 K.

Fig. 5.10 Spectra of a single-mode QC laser with a second generation AMZ interferometer type cavity ($\Delta L = 450 \mu m$) operated at various heat-sink temperatures (up to room temperature) in pulsed mode.

Pulsed LIV characteristics for the single-mode QC lasers with the second generation cavity designs are also taken at various heat-sink temperatures. The overall device performance for these lasers is much improved compared to the single-mode QC lasers with the first generation cavity design. As can be seen from the example presented in Fig. 5.11, the threshold current density for these single-mode QC lasers is relatively close to that of a FP cavity QC laser with similar cavity length, and their slope efficiencies are also comparable. The relatively low threshold current density suggests that the transitions between the straight waveguides and the curved waveguides with
constant large bending radius (300 µm) in the AMZ interferometer type cavities are essentially adiabatic and only small coupling loss and bend loss are introduced.

Fig 5.11 (a) Pulsed LIV characteristics of a QC laser with an AMZ interferometer type cavity (∆L = 450 µm) and cavity length of ~2.4 mm operated at 80 K. (b) Pulsed LIV characteristic of a FP cavity QC laser with cavity length of ~2.5 mm operated at 80 K.

The relatively low threshold current density also enables the CW operation of these single-mode QC lasers despite the fact that the device fabrication and packaging processes employed are not aimed for optimizing the CW operation. In addition, when these QC lasers are operated in CW mode in the sub-threshold regime, the spectra of the amplified spontaneous emission can be characterized in
high resolution using the FTIR, which in turn provides us with direct information on the wavelength selectivity associated with the AMZ interferometers. Figure 5.12 shows the spectra of the amplified spontaneous emission from such a device operated in CW mode at different sub-threshold conditions in comparison to the spectrum at the laser threshold current. The periodic envelope of the spectra with the expected periodicity (Eqn. 5.1) associated with the AMZ interferometer is clearly seen. At and above the threshold current, single-mode operation is achieved with the lasing mode corresponding to the strongest mode in the sub-threshold spectra. This can be considered as another evidence for the applicability of the theoretical model on AMZ interferometer type cavities presented in Section 5.2.

Fig. 5.12 Spectra of the amplified spontaneous emission from a QC laser with AMZ interferometer type cavity design ($\Delta L = 350 \, \mu m$) operated in CW mode at various sub-threshold conditions in comparison with the laser spectrum at the threshold current.
Fig. 5.13 (a) Spectra of a QC laser with AMZ interferometer type cavity (ΔL = 450 μm) operated in CW mode at 80 K and 120 K. (b) CW LIV characteristics of the same laser in (a) operated at 80 K and 120 K.

Much higher SMSR is achieved when these QC lasers are operated in CW mode than when operated in pulsed mode, which is attributed to the more stabilized operating conditions and device internal dynamics in CW mode. The spectra of such a laser with ΔL of 450 μm in its AMZ interferometer structure and a cavity length of ~2.1 mm operated in CW mode at 80 K and 120 K are shown in Fig. 5.13(a). Single-mode operation with ~35 dB SMSR is achieved. The CW LIV characteristics for this laser at the corresponding operating temperatures are plotted in Fig. 5.13(b).
The maximum output power is considerably lower than that obtained in pulsed operation, mainly due to the excessive device heating.

With even longer cavity and HR coating at the back-facet to reduce the laser threshold current density, CW single-mode operation can be achieved at even higher temperatures. Figures 5.14 shows that for another QC laser with $\Delta L$ of 450 $\mu$m and a cavity length of $\sim$2.7 mm, current-tunable CW single-mode operation with $\sim$35 dB SMSR is achieved from 80 K up to 160 K with large operating current range. This maximum CW operating temperature is mainly limited by the property of QC laser material itself (e.g., the active core design, waveguide loss, etc.) as well as the fabrication and packaging techniques employed (ridge waveguide with thin top metal contact, epitaxial side up mounted on copper heat-sink), but not significantly by the AMZ interferometer type cavity structures. Over the entire operating current range, the single-mode emission wavelength is continuously tuned piecewise and separated by occasional mode-hops or additional lasing modes. The laser spectra of the largest mode-hop free wavelength tuning range at each CW operating temperature is shown in Fig. 5.14(a)-(d), and the wavelength versus the pump current plots for the entire single-mode operating current ranges at the corresponding temperatures are shown in Fig. 5.14(e)-(h). Nearly 2 cm$^{-1}$ mode-hop free tuning range is achieved which should be sufficient for most single-species molecular sensing applications. However, the mode-hop free tuning range is expected to be significantly larger if the two arms of the AMZ interferometer are electrically separated and biased independently in a coordinating way, and it would eventually be limited by the periodicity of the transmission peaks associated with the AMZ interferometer. The CW LIV characteristics for the laser of Fig. 5.14 at different operating temperatures are plotted in Fig. 5.15. An interesting feature of the L-I curves is that they have relatively large fluctuations compared with those of conventional FP cavity lasers (the similar feature can also be seen in Fig. 5.13(b)). Part of such power instability can be accounted for by the change of the lasing modes, however, even in the current range where the emission wavelength is continuously tuned such power instability is still present, thus there could be other origins of the power modulation which are not yet well understood.
Fig. 5.14 (a)-(d) Spectra of a QC laser with AMZ interferometer type cavity design (ΔL=450 µm) and back-facet HR coating, operated in CW single-mode with large SMSR (~35 dB) at various heat-sink temperatures. (e)-(h) Emission wavelength vs. pump current for the entire single-mode operating current range at various heat-sink temperatures.
Fig. 5.15 CW LIV characteristics of the same laser in Fig. 5.14 operated at various heat-sink temperatures.

5.7 Discussions on Important Lessons Learned

The successful demonstration of CW single-mode operation with such AMZ interferometer type cavities comes as a result of several crucial steps of cavity design improvement, and some lessons have been learnt. One of the most important lessons learnt is that the adiabatic transitions between the curved waveguides and the straight waveguides are crucial since there are two such transitions at the two ends of an AMZ interferometer, and another four transitions in each arm of an AMZ interferometer, therefore, the total coupling loss can be overwhelming if the transitions are not properly designed. This lesson comes from the cavity designs shown in Fig. 5.16, in which curved sections with bending radius of 60 µm are employed in order to dramatically reduce the dimension of the AMZ interferometers. However, the tested devices do not reach lasing threshold even at very high pump current, and this is not due to any fabrication failure since the IV characteristics of the devices are normal and the facets of the devices are intact. We attribute such results to the high coupling loss and bend loss [25] introduced by the large-curvature waveguide structures.
Another lesson we have learnt is that the mode selectivity is not necessarily enhanced when two identical AMZ interferometers are cascaded as shown in Fig. 5.17. This is because although the peaks in the combined transmission spectrum associated with the two cascaded AMZ interferometers is narrower than that of one AMZ interferometer, the FSR of the cascaded cavity is also significantly smaller due to the much larger cavity length. The benefit for the narrowness of the transmission peaks is not enough to compensate for the reduction of the FSR for the cascaded AMZ interferometer type cavity structures, and therefore more (rather than less) neighboring FP modes within one transmission peak appear in the laser spectrum as can be seen in Fig. 5.18.
Fig. 5.18 Spectrum of a QC laser with cascaded AMZ interferometer type cavity. A number of modes within one transmission peak are observed. The FSR measured matches well the total cavity length.

5.8 Conclusion

In this project we have first proposed that the wavelength selectivity of AMZ interferometers can be exploited to facilitate single-mode operation of QC lasers and then developed the theoretical model for analyzing the mode profiles associated with the proposed cavity structures in which AMZ interferometers are monolithically integrated with straight ridge waveguides. We have further implemented a number of different AMZ interferometer type cavity designs with varying key design parameters and demonstrated that properly designed AMZ interferometers can introduce sufficient wavelength selectivity when monolithically integrated in conventional FP cavities, which in turn facilitates single-mode operation of the QC lasers. With such AMZ interferometer type laser cavities, continuously tunable single-mode operation of QC lasers with large operating current range is achieved in pulsed mode from 80 K up to room temperature and in CW mode with SMSR up to ~35 dB. QC lasers with such cavity structures are fabricated with the identical processes as simple ridge lasers, therefore is a promising solution to achieving more cost-effective single-mode QC lasers.

The work presented here should be seen as a proof-of-concept demonstration which hopefully would stimulate more future efforts on such an approach to commercially available cost-effective single-mode QC lasers, since the possibility for further optimization of the current cavity structures or
more original explorations of better cavity structures is far from exhausted. For example, the possibility of using AMZ interferometer structures with non-equal power splitting in the two arms (see Fig. 5.19(a)) should be studied, because it would allow for a dramatic reduction in the dimension of the AMZ interferometer and therefore improve the wavelength selectivity and minimize the FSR of the cavity modes at the same time. Having equal power in the two interferometer arms is not a necessary condition to achieving strong wavelength selectivity, although it gives the largest contrast between the transmission peaks and the valleys. Furthermore, interferometer structures with more than two arms (see Fig. 5.19(b)) are also promising investigation targets, for such interferometer structures offer additional degree of freedom to engineer the sharpness of the transmission peaks.

In short summary, AMZ interferometer type cavity based single-mode QC laser technology is a new and promising field for single-mode QC lasers with plenty of room for further explorations and developments.

Fig. 5.19 (a) Schematic of a proposed new AMZ interferometer design with asymmetric Y-splitter structures and therefore non-equal optical power in the two interferometer arms. (b) Schematic of a proposed new AMZ interferometer design with multiple (more than 2) interferometer arms.
References


Chapter 6

Conclusions

Mid-IR QC lasers are compact, powerful and reliable semiconductor light sources, ideal for a broad range of spectroscopic molecular sensing applications such as air quality and greenhouse gas monitoring, breath analysis for medical diagnostics, explosives and hazardous materials detection, etc. Even since the first demonstration of mid-IR QC lasers in 1994 after more than two decades of pursuit by generations of researchers, this emerging field has been expanding and developing rapidly at all levels, from fundamentals of the materials and the devices to QC laser based sensor systems and networks. The mid-IR QC laser technology has proven to be highly attractive and viable, thanks to QC lasers’ technological advantages over other competing technologies in mid-IR wavelength range as well as their extraordinary design flexibility. The research and the industrial communities have been collaborating closely for years, aiming to eventually realize compact, portable, power-efficient and cost-effective QC laser-based systems in various forms that can be deployed on a large scale to serve the society. To meet such ends, QC lasers as the cores of these systems have to be highly power-efficient, single-mode as well as cost-effective. However, the existing QC laser technology still lacks the capability to meet all these requirements simultaneously. Exploring novel approaches with an emphasis from the device design perspective to further advance the QC laser technology in all the aforementioned aspects is the focus this thesis and the related projects.

By employing a novel ultra-strong coupling strategy in designing the QC laser active core band-structures, we achieved a major step forward in the QC laser power performance, especially in the WPE, and a proof-of-concept mid-IR backscattering LIDAR was demonstrated by employing such a high performance ultra-strong coupling QC laser. This ultra-strong coupling design strategy was also successfully applied to realizing QC lasers with extremely broad-band optical gain spectrum.
In order to achieve single-mode QC lasers more cost-effectively, we proposed and then experimentally verified two fundamentally different approaches to introduce strong wavelength selectivity to the laser cavities and realized single-mode QC lasers that are compatible with simple ridge laser fabrication. The first approach was to employ a novel class of monolithic coupled-cavity structures, while the second approach was to monolithically integrate a properly designed AMZ interferometer structure in a FP cavity. The details of each project are summarized below, followed by an outlook for future development of the QC laser technology.

6.1 Ultra-strong coupling mid-IR QC lasers

Following the background introduction to mid-IR QC lasers in Chapter 1 including brief reviews of the history, the fundamentals and the various applications of QC lasers, we first did a thorough analysis in Chapter 2 on the key factors for the power performance of QC lasers and identified the crucial role of electron transport process in determining the device performance, especially the WPE. In conventional QC laser designs, one of the most critical steps in electron transport process is the resonant tunneling through the thick injection barrier between the injector and the downstream active region. The resonant tunneling rate is suppressed by several scattering mechanisms in a real QC laser device, and the interface roughness induced scattering is the dominant one. We modeled this resonant tunneling process under a density matrix formalism and discovered that due to the fast interface roughness scattering induced dephasing (which was long underestimated in the literature) and the insufficient (~3 meV) coupling strength between the injector ground state and the downstream upper laser state, the resonant tunneling process through the thick injection barrier in conventional QC laser designs is a bottleneck to the electron transport process and consequently hinders the population inversion. A straightforward solution to this issue is to employ a much larger (~10 meV) coupling strength between the injector ground state and the downstream
upper laser state to overcome the interface roughness scattering induced dephasing, which in turn is expected to greatly speed up the electron transport and improve the peak optical gain.

We employed such a novel ultra-strong coupling design strategy in real QC laser band-structure designs by dramatically reducing the thickness of the injection barrier and redesign the entire injector accordingly. In such designs, due to the much thinner injection barrier, the upper laser state partially extends into the injector and makes the radiative transition more diagonal and the upper laser state lifetime longer, which benefits the optical gain as well as the laser slope efficiency. We achieved a significant improvement in the laser power performance, especially in the slope efficiency, output power and WPE. The WPE reached ~50% in our best performing devices which set a new record when it was reported and was a major step forward compared to the previous record (~34%).

Besides improving the electron transport property and thus the device power performance, the ultra-strong coupling design strategy also allows for strong coupling of more than two spatially separated quantized states in a multiple QW structure such as a QC laser, therefore provides an alternative to achieving broad-band optical gain which is highly desired for applications such as multi-species sensing or mid-IR spectrometers. By combining the ultra-strong coupling and the short injector design strategies, we demonstrated a QC laser operating around 6.2 \( \mu \)m with an extremely broad optical gain spectrum. The FWHM of the optical gain spectrum is ~60 meV at 80 K and ~82 meV at 300 K, corresponding to ~30% and ~40% of the radiative transition energy, respectively, similar to the state-of-the-art broad-band optical gain QC lasers in the literature.

However, a major drawback associated with these ultra-strong coupling QC lasers is that the characteristic temperature is relatively low compared to some state-of-the-art conventional designs. Therefore, we have further investigated this issue systematically. We designed two pair of ultra-strong coupling QC laser designs. Within each pair, the two designs were almost identical except that in one design two electron exit barriers were designed to be taller using a different material composition. One pair of designs employs two resonant LO-phonon depopulation scheme while the other employs three resonant LO-phonon depopulation scheme. Comparing the device performance
within each pair and between the two pairs, we found that both the taller electron exit barriers and the larger energy defects contributed to the improvements in the characteristic temperatures and consequently the better performance at room temperatures of the corresponding ultra-strong coupling QC lasers.

6.2 Mid-IR backscattering LIDAR employing a high-performance ultra-strong coupling QC laser

Mid-IR backscattering LIDAR is a highly attractive technology because of its capability to extract the range and concentration information of relatively large aerosol particles in the atmospheric boundary layer which have significant impacts on the climate and human health. However, due to the lack of high-power laser sources in the mid-IR wavelength range, the development of mid-IR backscattering LIDAR systems was quite limited. However, with the performance of mid-IR QC lasers improving steadily over the years, a QC laser based mid-IR backscattering LIDAR systems became more and more feasible. Therefore, having performed the feasibility analysis and obtained positive results, we designed and tested a proof-of-concept horizontally oriented mid-IR backscattering LIDAR system employing one of the best performing ultra-strong coupling QC lasers. As presented in Chapter 3, backscattered signal from man-made plumes of water vapor at a distance up to 50 m away from the LIDAR system was detected with a SNR of more than 2. This was a very encouraging result for our LIDAR setup in the sense that it suggests a detection range of a few hundred meters with decent the SNR should be achievable since the SNR can be improved by orders of magnitude simply by performing signal averaging and increasing the repetition rate and/or width of the laser pulses. Hence, we redesigned the system to be vertically oriented and aiming at characterizing the profile of the relatively large aerosol particles in the atmospheric boundary layer (the lowest ~200 m range). New components were incorporated for resolving and analyzing the timing information in the backscattered signal. The entire system was built as a permanent setup in a lab dedicated for LIDAR measurement, and is currently being further optimized.
6.3 Single-mode QC lasers employing monolithic coupled-cavities

In order to address the issue of high cost associated with conventional single-mode QC lasers, e.g., DFB QC lasers and external cavity QC lasers, we first proposed in Chapter 4 to employ monolithic coupled-cavities making use of the building block consisting of a straight waveguide connecting to a curved waveguide with large curvature. As light travels along such a waveguide structure, reflection takes place at the geometrical boundaries between the two sections due to the transverse mode mismatch, and thus, though having no physical boundary in between, the two sections function as individual cavities and yet couple together. Then by applying this key idea, we implemented a number of different monolithic coupled-cavities with different shapes, e.g. hair-pin and candy-cane shapes, and structure details. Such laser cavities are compatible with simple ridge laser fabrication, thus can be fabricated cost-effectively. Continuously wavelength tunable single-mode operation of QC lasers with SMSR up to ~27 dB and large single-mode operating current range was achieved. The emission wavelength can be continuously tuned by changing the operating temperature or a DC bias current. By tailoring the device geometry such as the straight section length, the emission wavelength can be also shifted across a large range within the optical gain spectrum. However, a major downside for these monolithic coupled-cavities is that the mode coupling loss between the straight section and the curved section is quite large and therefore the threshold current density for these lasers is significantly higher than that of simple ridge lasers with similar cavity length. To address this issue, comprehensive modeling of the cavity mode profiles is necessary for further optimization of the cavity structures, which would be a focus of future work.

6.4 Single-mode QC lasers employing AMZ interferometer type cavities

We explored in Chapter 5 another approach to achieving single-mode QC lasers cost-effectively. By monolithically integrating a properly design AMZ interferometer structure into a FP cavity, a strong wavelength selectivity (mostly determined by the arm length difference $\Delta L$ of the
AMZ interferometer) is established which facilitates single-mode operation. Such a cavity structure is also compatible with simple ridge laser fabrication. The initial cavity designs based on this idea employed AMZ interferometers with $\Delta L$ ranging from 50 $\mu$m to 400 $\mu$m. It was observed that the larger $\Delta L$ was, the fewer lasing modes appeared, as expected from our modeling on such cavity structures. With the cavity design with $\Delta L=400$ $\mu$m, single-mode operation of QC lasers were achieved in pulsed mode. Then another generation of optimized cavity designs was implemented, with $\Delta L$ ranging from 350 $\mu$m to 500 $\mu$m and average arm length reduced to increase the cavity FSR. Single-mode QC lasers were realized with all the second generation cavity designs. The device performance was much improved in pulsed mode operation, and CW single-mode operation was also achieved, thanks to the relatively low coupling loss at the Y-splitters specifically designed for adiabatic transitions, with high SMSR of $\sim 35$ dB and continuously current tunable emission wavelength.

6.5 Outlook for the future directions of the QC laser technology

The QC laser technology has undergone a rapid and steady development ever since its beginning, and shows no sign of slowing down. As the technology becomes more and more mature, an increasing amount of efforts are also being invested in developing QC laser based commercial products, from laser chips and modules to sensor systems. For the time being, we are witnessing the take-off of a QC laser industry. One of the major propelling force for this industry is the constant improvement of the QC laser performance. With advancements in device structure designs, epitaxial growth technologies for current and new material systems, device fabrication and packaging technologies and so on, QC lasers are getting more powerful and power-efficient, covering wider spectral range, reaching broader wavelength tuning range in single-mode operation, becoming more cost-effective, etc. The work presented in this thesis focused on advancing the QC laser technology in most of the aforementioned aspects, and we hope that it will prove to be a valuable contribution. To
further improve the QC laser technology, the work presented here can be extended in at least the following directions.

First, the ultra-strong coupling design strategy should be further optimized and combined with other design strategies to further improve the temperature characteristics of ultra-strong coupling QC lasers. For example, it has been recently discovered that interface roughness induced intersubband scattering is a dominant process (comparable to LO-phonon scattering) in mid-IR QC laser operations, and it is possible to engineer the scattering lifetimes by strategically positioning additional thin layers of materials and thus interfaces in the band-structure designs of QC lasers [1]. Understanding the implication of this discovery to the ultra-strong coupling design strategy (as well as conventional designs) and the new possibility it brings are crucial tasks for the further optimization of the ultra-strong coupling design strategy. With even higher performance QC lasers, applications such as mid-IR backscattering LIDAR systems will undergo energetic development.

Furthermore, the broad-band optical gain QC lasers employing both ultra-strong coupling and short injector design strategies can be employed as the gain medium of an external cavity QC laser, in order to achieve extremely broad single-mode wavelength tuning range. On the other hand, they can also be explored to realize a QC laser based mid-IR frequency comb [2] which would motivate many new applications for mid-IR QC lasers.

In addition, the power performance of monolithic coupled-cavity QC lasers should be further improved. Optimizations of the cavity designs with assistance from comprehensive modeling on such cavity structures may prove to be a viable path. Currently, the major challenge is the large transverse mode coupling loss at the geometrical boundaries between different sections of the cavity. A possible solution is to find and achieve a more optimized trade-off between the reflectivity and the mode coupling loss at such geometrical boundaries by accurate modeling and appropriate cavity design optimizations.

Last but not least, more explorations on the AMZ interferometer type cavity structures should be conducted. The major goals for such further explorations include increasing the continuous single-
mode wavelength tuning range and scaling down the device footprint. The AMZ interferometer type cavity introduced a rich design space with plenty of room for further optimization. Some examples of exploration directions are given in Chapter 5, nevertheless, many other possibilities are expected. Both the AMZ interferometer type cavity and the monolithic coupled-cavity have the crucial technological advantage of relatively low fabrication requirements, and therefore may become key solutions to low-cost commercial single-mode QC lasers.

In short, the QC laser performance can be further improved in many directions through various approaches, and the QC laser industry has a bright future with many possibilities.
References


Appendix A

Experimental Setups for QC Laser Characterizations

A1. Experimental setup for pulsed LIV characterization

The pulsed LIV characterization setup mainly consists of a pulse generator (Avtech AVL-2B), a 50 $\Omega$ resistor for impedance matching, an oscilloscope (Lecroy Wavepro 7300A), a current probe (Integrated Sensor Technologies 711), two AR coated ZnSe lenses (1.5 inches focal length, 2 inches diameter), a room temperature MCT detector (Vigo PEM-10.6) and a preamplifier (Sonoma Instruments 310). Both the MCT detector and the cryostat housing the QC lasers are mounted on 3-axis translation stages. The entire setup is illustrated in Fig. A1.

Fig. A1 Schematic of the pulsed LIV characterization setup.
Current pulses from the pulse generator drives the QC laser housed in a cryostat. Signals representing the current flow through and the voltage drop on the QC laser are sent into the oscilloscope. Laser beam from the QC laser is collimated by the first lens and then focused onto the detector by the second lens. The detector signal is sent to a preamplifier and then passed to the oscilloscope. The oscilloscope then sends the averaged data of the current, voltage and light power to the computer.

A2. Experimental setup for CW LIV characterization

The CW LIV characterization setup mainly consists of a source meter (Keithley 2420), a multimeter (Keithley 2000), a thermopile (Coherent LM-3 HTD) with its compatible power meter (Coherent Labmax TO), two AR coated ZnSe lenses (1.5 inches focal length, 2 inches diameter). Both the power meter and the cryostat housing the QC lasers are mounted on 3-axis translation states. The entire setup is illustrated in Fig. A2.

Fig. A2 Schematic of the CW LIV characterization setup.
DC current from the source meter drives the QC laser housed in a cryostat. Data of the DC current and voltage applied are sent into the computer from the source meter. The laser beam from the QC laser is collimated by the first lens and then focused onto the thermopile by the second lens. The thermopile signal is sent to a compatible power meter for conversion and then passed to the multimeter. The multimeter further relays the data to the computer.

A3. Experimental setup for laser and EL spectrum characterization

The laser driving circuits for both pulsed mode and CW mode operations in the spectra characterization setup are similar to those in the LIV setups, except for a different pulse generator (Agilent 8114A). The setup also employs a different oscilloscope (Tektronix TDS 3054C). The characterization of mid-IR spectrum is performed with a FTIR (Thermo Nicolet Nexus 870). The cryostat housing the devices is mounted on a 3-axis translation stage, and light is collimated with an AR coated ZnSe lens (1.5 inches focal length, 2 inches diameter) and sent into the FTIR. For EL spectrum characterization, a lock-in amplifier (EG&G Princeton Applied Research 5210) is employed to extract the weak periodic signal out of the strong environmental background. The setups for laser and EL spectrum characterizations are illustrated in Fig. B3(a) and (b), respectively.
Fig. A3 (a) Schematic of the QC laser spectrum characterization setup. (b) Schematic of the QC structure EL spectrum characterization setup.

For characterizing the laser spectrum, the laser is operated in either pulsed or CW mode by the driving circuits described in A1 or A2. The laser beam is collimated by the ZnSe lens and sent into the FTIR. The FTIR automatically measures the laser spectrum and sends the data to the computer.

For characterizing the EL spectrum, the device is operated in either pulsed or CW mode by the driving circuits described in A1 or A2. The generated EL is collimated by the ZnSe lens and sent into the FTIR. The signal from the internal detector of the FTIR is forwarded to an lockin amplifier, and the extracted signal is sent back to the FTIR, which automatically resolves the EL spectrum and sends the data to the computer. If the device is operated in CW mode, an optical chopper (not shown in Fig. A3(b)) needs to be applied to periodically modulate the EL signal, so that the lockin amplifier functions properly.
Appendix B

Summary of the Ultra-strong Coupling QC Lasers

Table B1 Summary of the 12 ultra-strong coupling QC designs and some characterization results

<table>
<thead>
<tr>
<th>Wafer No.</th>
<th>λ (µm)</th>
<th>Sheet doping (cm⁻²)</th>
<th>No. of periods</th>
<th>FWHM (80K) (meV)</th>
<th>FWHM (300K) (meV)</th>
<th>Eₘₚ (80K) (meV)</th>
<th>Eₘₚ (300K) (meV)</th>
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Table B2 Summary of the laser characterization results of the 12 ultra-strong coupling QC designs

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<tr>
<th>Wafer No.</th>
<th>Jₘₚ (80K) (kA/cm²)</th>
<th>Jₘₚ (300K) (kA/cm²)</th>
<th>T₀ (K)</th>
<th>S (80K) (W/A)</th>
<th>S (300K) (W/A)</th>
<th>Max WPE (80K)</th>
<th>Max WPE (300K)</th>
<th>αₑ (80K) (cm⁻¹)</th>
<th>gΓ (80K) (cm/kA)</th>
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<td>7.9</td>
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<td>16.0</td>
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<td>8.7</td>
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<td>47.3%</td>
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<td>1.5</td>
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<td>8.8</td>
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List of symbols in Table B1 and Table B2:

λ: average emission wavelength

FWHM: full width at half maximum of the EL spectra

E_{def}: energy defect

J_{th}: threshold current density

T_0: characteristic temperature

S: slope efficiency

α_w: waveguide loss

gΓ: modal gain coefficient
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