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ISSN 1870-9095

Novel emerging concepts and applications of Quantum Cascade Lasers in research

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(Received 1 July 2024, accepted 31 August 2024**)**

Abstract

The field of Quantum Cascade Lasers (QCLs) has recently grown very rapidly due to the fact that these lasers are having great advantages over the other semiconductor lasers, and consequently have found newer applications. The design and development of QCLs is strongly based on the wavelength of operation, power required, the number of modes, and also the CW mode of operation, as all these parameters have long ranges, and the final choice is mainly determined by their applications, which requires lot of experience and expertise on the part of the opticist designing the device using such lasers. This paper presents the technical analysis of these parameters and also an overview of the important experimental results available in the literature. It is hoped that the paper should be useful for the designers and the engineers in this evolving field.

Key Words: Quantum Cascade Lasers, Quantum wells, High power CW Room Temperature.

Resumen

El campo de los láseres de cascada cuántica (QCL) ha crecido muy rápidamente recientemente debido al hecho de que estos láseres tienen grandes ventajas sobre los otros láseres semiconductores y, en consecuencia, han encontrado aplicaciones más nuevas. El diseño y desarrollo de los QCL se basa en gran medida en la longitud de onda de operación, la potencia requerida, el número de modos y también el modo de operación CW, ya que todos estos parámetros tienen rangos largos y la elección final está determinada principalmente por sus aplicaciones, lo que requiere mucha experiencia y conocimientos por parte del óptico que diseña el dispositivo que utiliza dichos láseres. Este artículo presenta el análisis técnico de estos parámetros y también una descripción general de los resultados experimentales importantes disponibles en la literatura. Se espera que el artículo sea útil para los diseñadores e ingenieros en este campo en evolución.

Palabras clave: Láseres de cascada cuántica, pozos cuánticos, onda continua de alta potencia a temperatura ambiente.

I. QUANTUM CASCADE LASERS AND EMERGING CONCEPTS

Quantum cascade lasers are based on quantum properties, which result from the structuring of semiconductor multilayers. Their development relies on progress, both in the fundamental physics of semiconductor heterostructure and in the technology of epitaxial growth of the structures. A QCL is made of a heterostructure grown by molecular beam epitaxy (see Molecular Beam Epitaxy- Fig. 1). It consists of a large number of nanometer-scale layers of two different materials, embedded between two optical confinement layers.

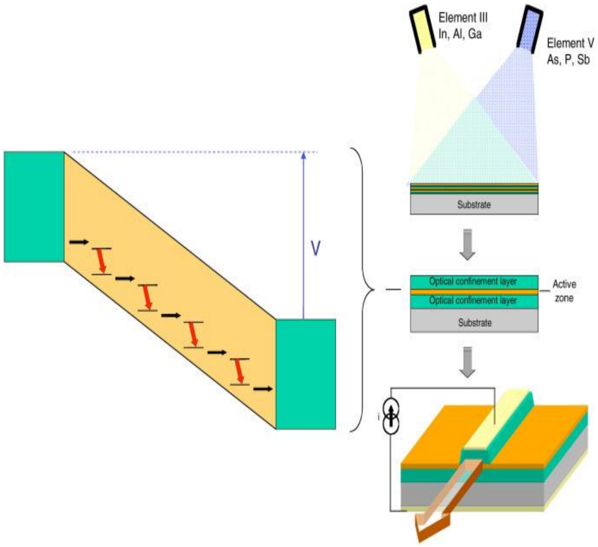


FIGURE 1. Schematic of the structure of a QCL. *Figure courtesy* https://resources.pcb.cadence.com, Quantum Well Design Basics | Cadence.

The quantum cascade lasers (QCLs) are special kind of semiconductor lasers [1, 2], usually emitting light in the mid-IR spectral region, which operate differently from the conventional semiconductor lasers, as the laser transitions are based on the intersubband transitions in a repeated stack of semiconductor multiple quantum well heterostructures, instead of those between the different electronic bands. The Schematic of the gain region of a quantum cascade laser is shown below:

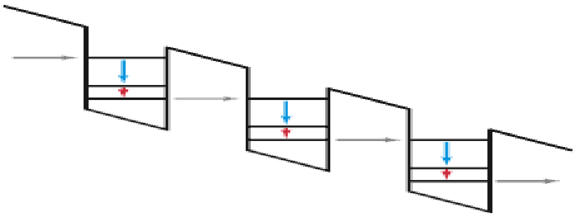


FIGURE 2. Schematic of the gain region of a quantum cascade laser, showing the electron energy vs. position in the structure, containing three quantum wells. Figure courtesy http://www.rp-photonics.com/quantum_cascade_lasers.html.

It is observed that there is an overall downward trend of energy towards the right-hand side. This is explained as being caused by an applied electric field. Also, each gain region is considered to be divided into an active region and an injector. An electron injected into the gain region, in each period of the structure, undergoes a first transition (upper arrow) between two sublevels of a quantum well - the laser transition on which the stimulated emission takes place, followed by a non-radiative transition (lower arrow) to the lowest sublevel, before finally tunneling (right horizontal arrow) into the upper level of the next quantum well. Interestingly, by using a cascade of quantum wells (several tens or even 100), a higher optical gain is achieved along with the multiple photons per electron, though at the expense of a higher required electrical voltage. It is important to note that the operation voltage can easily be ~ 10 V, whereas much lower voltage (few volts) is sufficient for the conventional laser diodes.

A very special characteristic of the QCLs is that it is possible to design these for operating wavelengths in a wide range (from a few microns to much higher than 10 μm, and even in the THz region, because of the fact that the transition energies are defined by design parameters, especially layer thickness values of quantum wells, and not by the fixed material properties. In a QCL, the quantum well structure is embedded in a waveguide, and the laser resonator is usually of Distributed Bragg Reflector (DBR) or Distributed Feedback (DFB type). Another design is that of the external-cavity lasers, which has a wavelength tuning element e.g. a diffraction grating, as a part of the resonator.

For the case of CW operation, the room-temperature devices (5) have moderate output power levels in the milliwatt region, though in some cases, more than a watt is also possible. However, with liquid-nitrogen cooling, an output of multiple watts is easily possible. Also, at room temperature, watt-level peak powers are achievable for the case of lasing in the form of short pump pulses. Though, the power conversion efficiency of QCLs is ~ 20%-30%, some devices with efficiencies ~ 50% have recently been demonstrated [3, 4] only for the cryogenic operation conditions. Quantum cascade lasers have been found to be quite promising mid-**IR** semiconductor light sources for molecular detection in applications like environmental sensing or medical diagnostics, for which researchers have been trying to improve the device performance. Liu et al. [3] have reported that an ‘ultrastrong coupling’ design strategy leads to the experimental realization of quantum cascade lasers with 40–50% wall plug efficiency (the portion of the injected electrical energy that can be converted into output optical energy, considered one of the most important figures of merit when operated in pulsed mode at temperatures of 160 K or lower. Bai et al. [4] have demonstrated 53% wall plug efficiency at 40 K with an emitting wavelength of 5 μm, i.e. designed quantum cascade laser, which produces more light than heat. QCLs can also be fabricated for generating terahertz waves, and these devices are very compact and simple sources of THz radiation. Interestingly, these terahertz waves can also be generated at room temperature by internal difference frequency generation. Belkin et al. [5] have reported on their progress in the development of a THz quantum cascade laser source based on intracavity terahertz difference-frequency mixing in a dual-wavelength mid-infrared quantum cascade laser with the active region engineered to possess giant second-order nonlinear susceptibility. Also, they have demonstrated devices operating in mid-IR at λ_1=8.9μm and λ_2=10.5μm, and have produced terahertz output at $\lambda \approx 60$μm via difference-frequency generation with 7μW output power at 80K, 1μW output at 250K, and ~ 300nW output at 300K.

II. THEORY AND SOME EXPERIMENTAL RESULTS

The QCLs are based on the working of the quantum well (QW), which is a thin layer, capable of confining particles - electrons and holes in the dimension perpendicular to the layer surface, though the movements of particles in the other dimensions are not res

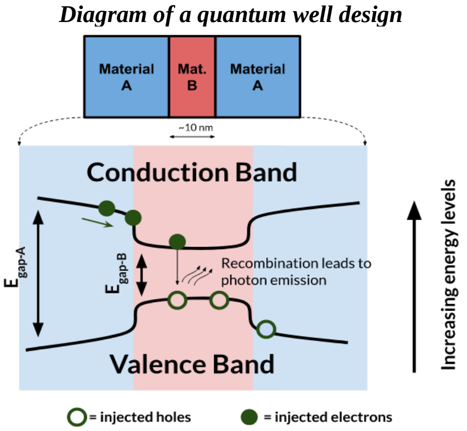


FIGURE 3. Diagram of a quantum well design. Figure courtesy https://resources.pcb.cadence.com, Quantum Well Design Basics | Cadence.

In a quantum well design, material B (like GaAs) is sandwiched between material A (such as AlGaAs), creating a potential well (from the two different bandgap differences) that confines electrons in the conduction band or holes in the valence band. A quantum well design consists of a type of heterostructure characterized by a thin layer, referred to as the "well," that is sandwiched by two thicker "barrier" layers. This configuration is named because electrons and holes experience reduced energy within the well layer, similar to objects settling at the bottom of a potential well. In a quantum well design, material B (like GaAs) is sandwiched between material A (such as AlGaAs), creating a potential well (from the two different bandgap differences) that confines electrons in the conduction band or holes in the valence band. The QCL active zone is a periodic structure (20–50 repeats) of a pattern similar to the one presented in Fig. 4. When an electrical bias is applied, the QW confined levels of the injector region align. It leads to electron injection into the excited level (*e*3) of the active QW. Through this mechanism, population inversion can be achieved between *e*3 and the lower level (*e*2), providing intersubband optical gain. In this unipolar device, electrons flow sequentially through each period (this is the cascade scheme); thus, one electron can emit several photons.

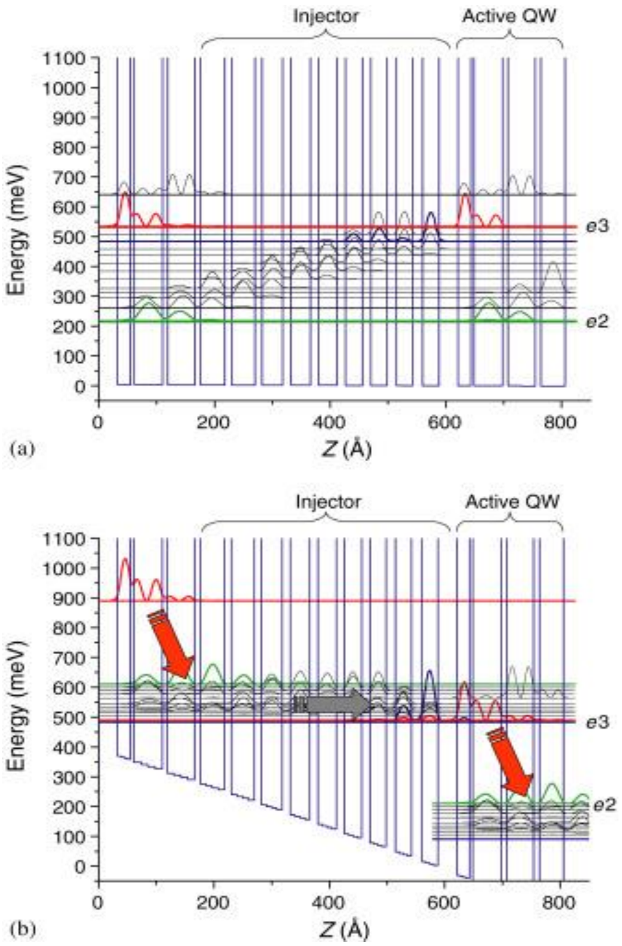


FIGURE 4. Conduction band profile and wave functions (moduli squared) of the relevant electron levels of one period of a QCL active zone at (a) zero bias and (b) working bias. Figure courtesy sciencedirect.com.

In the same way, as in classical semiconductor injection lasers, the laser optical cavity is a ridge waveguide made by etching of the top optical confinement layer and closed by the cleaved front and rear facets.

The Quantum Well Laser (QWL) consists of the middle active layer quite thin (~5nm to 20nm), and quantum well height reduced so as to be able to confine the electrons. On the basis of number of materials used, a layer of low band gap material, embedded between two higher band gap material layers. Each of the junctions between different band gap materials is called a double heterostructure, due to the presence of two junctions. Heterostructure Laser is designed to confine light more effectively, which is done by adding two more layers. The designs of a Quantum Well Laser (QWL), and Double Heterostructure are shown below:

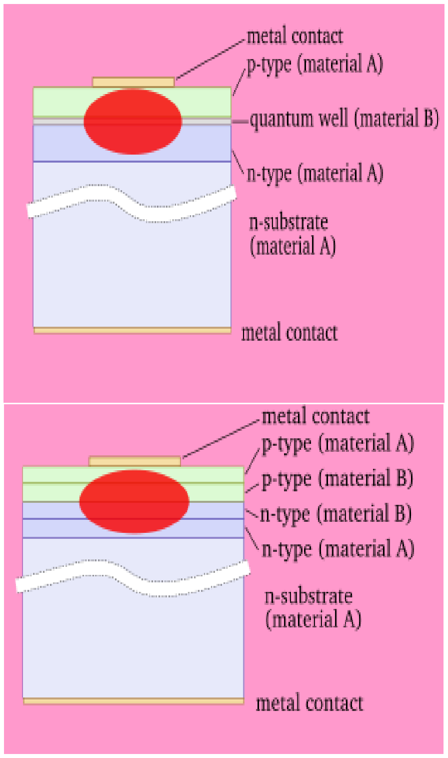


FIGURE 5. Design of Quantum Well Laser (Top); and Design of a Double Heterostructure (Bottom). Figure courtesy sciencedirect.com.

It has be understood that the outer layers have lower refractive index than the central layer. A quantum well has three layers- two outer layers of high band gap material, and the inner layer of low band gap material. The structure can be fabricated in two ways: (i) Molecular beam epitaxy (MBE), and (ii) Chemical vapor deposition (CVD). The quantum cascade lasers have an important application in the area of spectroscopy of trace gases, e.g. for detecting very small concentrations of pollutants in air. Their other applications are based on the characteristics: the suitable wavelength range, a relatively narrow linewidth, and good wavelength tunability.

Thus, the QCL is a semiconductor laser, with characteristics quite different from the conventional semiconductor lasers. A conventional semiconductor laser absorbs light when electrons are excited from the valance band to the conduction band, and the light is emitted when those electrons drop into the valance band. So, construction wise, the conventional semiconductor laser has the active region, which consists of two semiconductor materials forming a p-n junction, and the injected electrons and holes in the active region recombine and create photons. This operation is made clear in the figure given below:

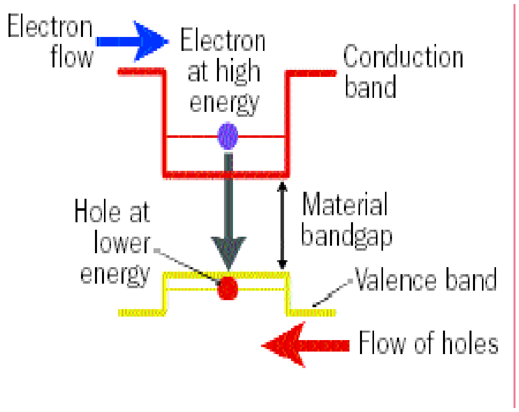


FIGURE 6. Illustration of the working of the conventional semiconductor laser. Figure courtesy sciencedirect.com.

There are some disadvantages of the conventional semiconductor lasers:(i) The band gap decides the wavelength of the laser, and so to get the laser with different wavelength, we have to choose a different material; and (ii) once an electron has emitted a laser photon by jumping from the upper to the lower energy level, it remains in the valence band. Some of the disadvantages are overcome by using the QCLs, which rely only on one type of carrier- the electrons, thus being called the unipolar lasers; and the photon emission therefore relies on intraband transitions between quantized conduction band states in coupled quantum wells. The Quantum wells are ultra thin sandwiches of two different semiconductors. In fact, a quantum well is essentially a semiconductor with relatively low band gap energy sandwiched between semiconductor layers with high band gap energies. Interestingly, the thickness is ~ a few nanometers, and electrons are confined primarily to the central part of the sandwich. In this case, the energy levels are in the form of series of discrete energy levels, whose separation is controllable by changing the thickness of the quantum-well layers.

Therefore, in QC lasers, the wavelength can be tailored over a wide spectral region, the entire mid infrared to the far-infrared, and also, once an electron has emitted a laser photon by jumping from the upper energy level to the lower energy level, it remains in the conducting band, and it is recycled there by injection into an adjacent identical stage, where a second photon is emitted, and so on, creating as many laser photons. The material systems - AlInAs/GaInAs and GaAs/AlGaAs have been used for the different lasers developed in this category, both the structures consisting of a periodic repetition of two regions, an injector and a coupled quantum well active region.

In a bulk semiconductor crystal, electrons occupy states in one of two continuous energy bands - the valence band, heavily populated with low energy electrons, and the conduction band, sparsely populated with high energy electrons, the energy bands being separated by an energy band gap, having no permitted states for the electrons to occupy. In case of conventional semiconductor laser diodes, light is generated by a single photon being emitted when a high energy electron in the conduction band recombines with a hole in the valence band, which implies that the energy of the photon and hence the emission wavelength of laser diodes, is determined by the band gap of the material system used.

However, a QCL does not use a bulk semiconductor material in it's optically active region, and in fact consists of a periodic series of thin layers of varying material composition forming a superlattice, which introduces a varying electric potential across the length of the device, and hence there is a varying probability of electrons occupying different positions over the length of the device. This confinement is referred to as 1-D multiple quantum well confinement, which leads to splitting of the band of permitted energies into a number of discrete electronic subbands. The population inversion between two subbands in the system is achieved by suitable design of the layer thicknesses. The fact that the position of the energy levels in the system is mainly determined by the layer thicknesses, and not the material, makes it possible to tune the emission wavelength of QCLs over a wide range in the same material system.

Another difference is that whereas, in semiconductor laser diodes, electrons and holes are annihilated after recombining across the band gap, and can play no further part in photon generation in a unipolar QCL, once an electron has undergone an intersubband transition and emitted a photon in one period of the superlattice, it can tunnel into the next period of the structure, resulting in the emission of another photon. In this way, a single electron can cause the emission of multiple photons, during it's traversal through the QCL structure (*N* photons when it traverse *N* stage cascade structure) , which is why this laser is called cascade This also leads to the possibility of making the quantum efficiency greater than unity, which in turn leads to higher output powers as compared to those achieved by semiconductor laser diodes. Other advantages of the QCLs are: the Low failure rate, robust fabrication and long life time.

The design and development of the high power, room temperature QCLs operating in pulsed mode (Fig.7a), and the high temperature, liquid nitrogen cooled QCLs operating in continuous mode (Fig.7b) have already been reported, and some of these results have been reproduced below:

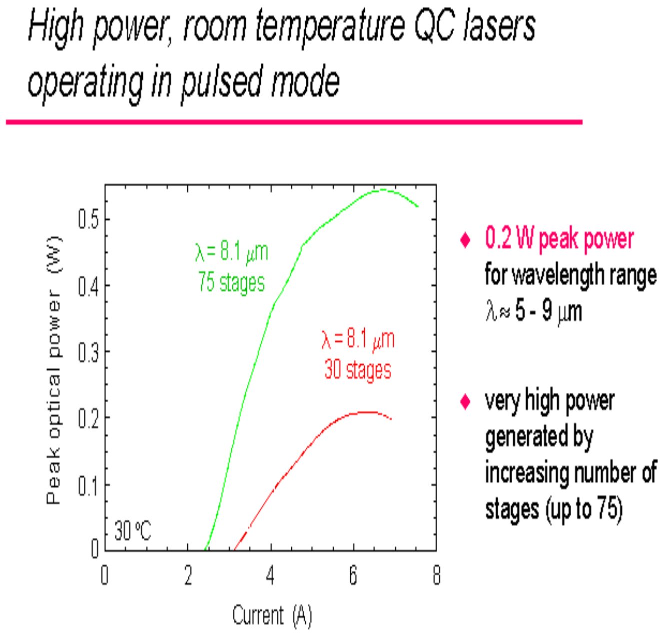


FIGURE 7(a).High power, Room temperature QCLs operating in pulsed mode.

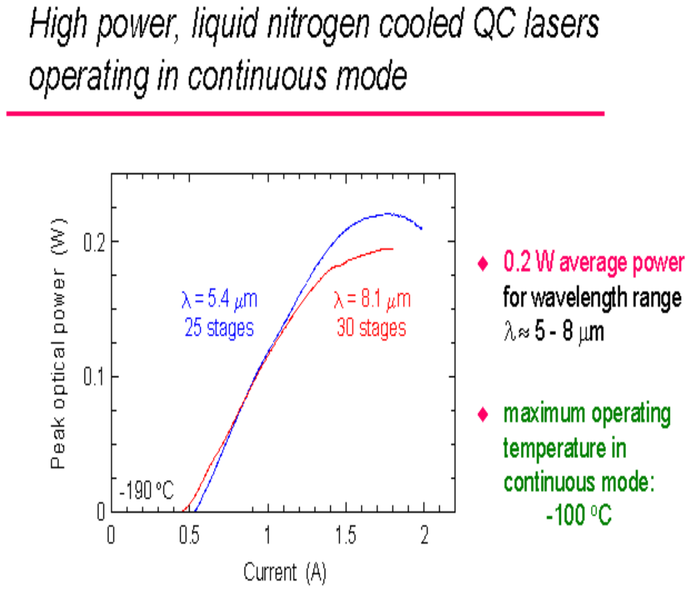


FIGURE 7(b). High temperature, Liquid nitrogen cooled QCLs operating in continuous mode. Figure courtesy Jayakumar H., Optical communication Seminar.

III. MATHEMATICAL MODELING OF QCLs

The mathematical modeling of QCLs is based on optimizing many parameters namely; threshold current density, reciprocal cavity length (1/*L*), mirror loss, the facet reflectivity, the gain coefficient, and the overlap factor of the active region. All these parameters are optimized to minimize the waveguide losses αW, which in QC lasers are typically characterized using two independent methods: one based on a plot of the threshold current density versus reciprocal cavity length (1/*L*) and the other on an analysis of subthreshold emission spectra for different injected currents. The former method (6) is based on the threshold condition, which can be written as:

$$J_{th} = (\alpha_W + \alpha_M)/(g\Gamma AR) = \{(\alpha_{LW})/(g\Gamma AR) - \ln(R)/(g\Gamma AR)(1/L)\}, \quad (1)$$

where $\alpha_M = -\ln(R)/L$ is the mirror loss, *R* is the facet reflectivity (= 0.27) and g is the gain coefficient.

The net modal gain *(NMG)* is given by:

$$(NMG) = \{GM(\lambda) - \alpha W\}, \quad (2)$$

and

$$(GM\lambda) = Jg(\lambda)\Gamma AR, \quad (3)$$

where *J* is the current density, and *g(λ)* is the gain coefficient as a function of the wavelength, which is extracted from the fringe contrast using numerical Fourier analysis of the subthreshold spectra. So, the net modal gain has to be maximized by optimizing the values of *J* and *g*(λ).

It has to be noted that the results obtained after the synthesis are generally different from those based on theory; and so lots of corrections have to be applied after getting the measurements, which requires a lot of software skill and the design experience. Quantum design of all laser properties is done through designing of parameters like wavefunctions, matrix elements, and relaxation times.

Another important case is that of narrow ridge-waveguide interband cascade lasers. The gain within a given waveguide required to reach the lasing threshold is given by the equation:

$$g_{th} = \{(\alpha_{wg} + \alpha_{mirr})/\Gamma\}, \quad (4)$$

where α_{wg} is the waveguide loss, α_{mirr} is the mirror loss, and Γ is the optical confinement factor. The mirror loss is due to photons escaping through the mirrors of the optical resonator. Waveguide losses can be due to absorption in the active, separate confinement, optical cladding materials, and metal contacts (if the claddings are not thick enough), or result from scattering at the ridge sidewalls.

The confinement factor is that percentage of the optical energy concentrated in the cascade stages. As with other semiconductor lasers, ICLs have a tradeoff between optical loss in the waveguide and *Γ*. The overall goal of waveguide design is to find the proper structure that minimizes the threshold gain. The Light-current characteristics in continuous-wave mode at room temperature for narrow ridge-waveguide interband cascade lasers with several different ridge widths (*w*) as reported (7) in the literature are reproduced below:

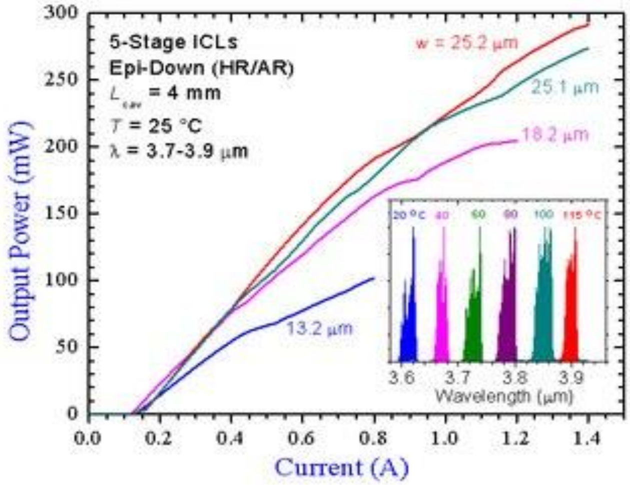


FIGURE 8. Light-current characteristics in continuous-wave mode at room temperature for narrow ridge-waveguide interband cascade lasers with several different ridge widths (w) as indicated in the figure. At the maximum output power, the beam quality is within ≈2 times the diffraction limit for all the ridges. The cw lasing wavelength of these ICLs spans from 3.6 to 3.9 µm in temperature range from 20 to 115 °C (as shown in inset). The figure on the right shows the performance characteristics of narrow ridge-waveguide interband cascade lasers at room temperature operating in cw mode. Figure courtesy Bewley, W.W., Canedy C.L., Kim C.S., Kim M., Merritt C.D., Abell J., Vurgaftman I., and Meyer J.R. (2012). "High-power room-temperature continuous-wave mid-infrared interband cascade lasers". Optics Express. 20 (19): 2089420901. Bibcode:2012OExpr..2020894B. doi:10.1364/OE.20.020894. PMID 23037213.

The term Quantum confinement refers to the condition, when electrons and holes in a semiconductor are restricted in one or more dimensions e.g. A quantum well is confined in one dimension. Based on the Heisenberg uncertainty principle, Quantum confinement effect can be given by:

$$E_{confinement} = \{(\Delta p_X)^2 / 2m\} \sim \{ h^2 / 2m(\Delta x)^2\}, \qquad (5)$$

where $\Delta p_X \sim (h / \Delta x)$.

If the design can be such that confinement > 1/ (2 $k_B T$), we have

$$\Delta x \sim \lambda_{deB}, \qquad (6)$$

where λ_{deB} is the de Broglie wavelength. Thus, the Quantum size effects are important, when $\Delta x \sim 5$ nm ($m_e^* = 0.1\, m_0$, electrons in semi-conductor at *RT*).

In general, a single GaAs/AlGaAs quantum well is formed in the thin GaAs layer sandwiched between AlGaAs layers, which have a large band gap. The parameter *d* is chosen so that the motion of the electrons in the GaAs layer is quantized in z direction. A quantum well is confined in one dimension or two dimensions. There are three basic types of quantum confined structure A quantum dot is confined in zero direction, or in three dimensions. These are illustrated in the following figure:

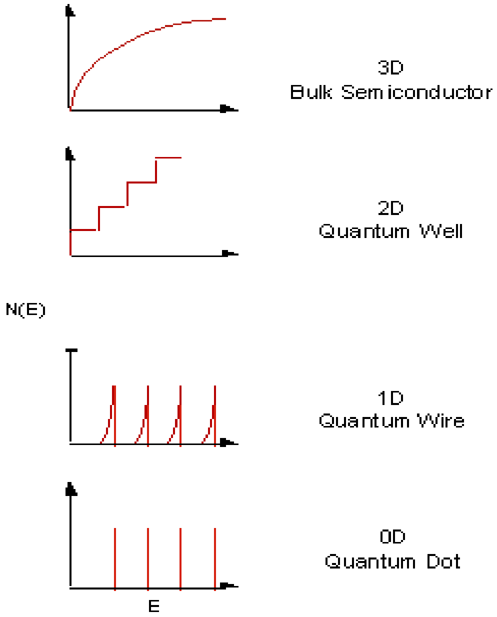
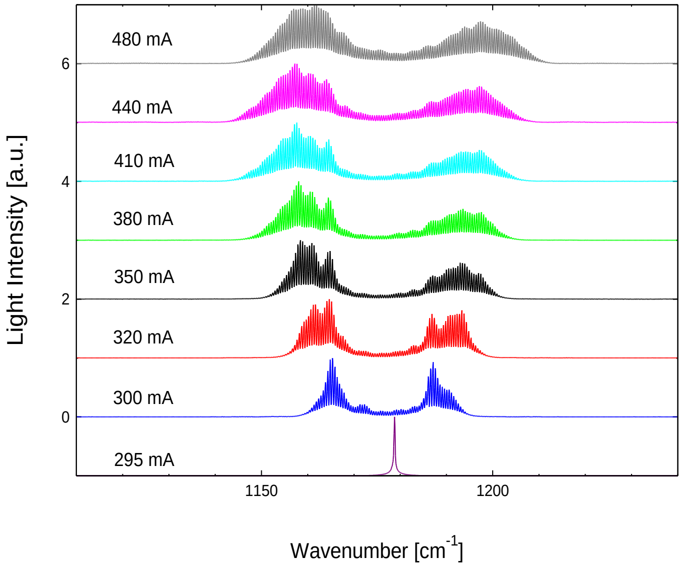


FIGURE 9. Quantum confinement in Quantum Wells and Quantum Dots.

Some exciting research opportunities in high power QCLs have been noticed, and found useful. For example, High Power QC lasers have been found to be a unique system to study (i) quantum transport in the presence of high static electric fields $10^4 - 10^5$ V/cm) and high radiation fields ($>10^4$ V/cm); and Photon driven transport, (ii) the AC Stark effect and it's effect on transport and resonant tunneling, and (iii) Coherent regime, in which Rabi frequency is greater than dephasing frequency: inversion is modulated at the Rabi frequency, leading to parametric laser gain at sidebands of Rabi frequency. Some very exciting results of variation of light intensity (au) with wave number (cm^{-1}), and frequency (THz) with power ^1/2(mW$^{\wedge 1/2}$) have been reported in the literature, which have been reproduced below:



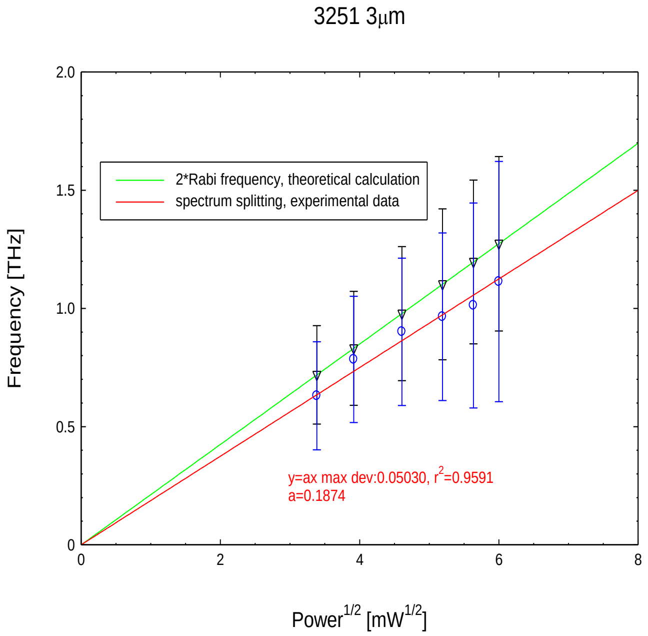


Figure 10. lustration of new phenomena in high Power QC lasers (variation of light intensity (au) with wave number ((cm^{-1})) – (Top), and frequency (THz) with with power ^1/2(mW$^{1/2}$– (Bottom), Figure courtesy, Capasso Federico, Division of Engineering and Applied Sciences, Harvard University capasso@deas.harvard.edu.

The quantum well structure is used in the electronic devices, with the main commercial application based on: (i) A greater range of emission wavelength; and (ii) An enhancement of device efficiency. The general equation for emission estimation is given by:

$$E=\{AxEFX(1-ER/100)\}. \qquad (7)$$

where E = emissions, A = activity rate, EF = emission factor, and ER = overall emission reduction efficiency (%). For calculating the Emission spectrum for QW, (i) The $(hv\ -E_g)^{1/2}$ factor is replaced by the unit step function derived from the 2-D density of states; (ii) The peak at energy: $hv=E_g+E_{hh1}+E_{e1}$, is shifted by the quantum confinement of the electrons and holes to higher energy; and (iii) spectral width ~ k_BT.

IV. CONCLUDING REMARKS

The field of Terahertz quantum cascade lasers (QCLs) has been drawing the interest of various workers [8, 9, 10, 11] during the last decade. Hugi et al. [12] *have* presented the development of a broad gain quantum cascade active region. By appropriate cascade design and using a symmetric active region arrangement, they have engineered a flat gain and have increased the total modal gain in the desired spectral range. It has been reported that (i) Grating-coupled external cavity quantum cascade lasers using this symmetric active region are tunable from 7.6 to 11.4 μm with a peak optical output power of 1 W and an average output power of 15 mW at room-temperature; and (ii) With a tuning of over 432 cm−1, this single source covers an emission range of over 39% around the center frequency. Maulini et al. [13] have presented a quantum-cascade structure based on a bound-to-continuum design exhibiting a broad gain curve, and have reported the full width at half maximum of the measured luminescence spectrum as 297cm^2 lumen at room temperature. The other findings of their work are that (i) the Grating-coupled external cavity lasers using this active region can be tuned over 150 cm^2 lumen ~1.45 mm, which is equal to 15% of the free running wavelength (l>10 mm), in pulsed mode at room temperature; and (ii) Time resolved spectra shows a single-mode operation with a 30dB side mode suppression ratio after the first 12 ns of the pulse. Phillips and Hô [14] have recently demonstrated a versatile mid-infrared hyperspectral imaging system by combining a broadly tunable external cavity quantum cascade laser and a microbolometer focal plane array. By using the tunable midinfrared laser providing high brightness illumination over a tuning range from 985 cm^{-1} to 1075 cm^{-1} (9.30–10.15 μm), hypercubes containing images at 300 wavelengths separated by 0.3 cm^{-1} have been obtained in 12 s. High spectral resolution chemical imaging of methanol vapor has been demonstrated for both static and dynamic systems, and the system has also been used to image and characterize multiple component liquid and solid samples.

Kumar [15] has recently presented a report, which describes the recent progress in phonon-depopulated terahertz QCLs. He has stated that the operation above 160 K has been realized in GaAs/AlGaAsbased QCLs with metal-metal waveguides for frequencies ranging from 1.8-4.4 THz (λ ~ 170-70 μm), and that a record highest operating temperature of 186 K has been demonstrated for a 3.9-THz QCL based on a diagonal design scheme, in addition to achieving the operation down to a frequency of 1.45 THz (λ ~ 205 μm). It has been emphasized that the metal-metal waveguides provide strong mode confinement and low loss at terahertz frequencies, and obtaining single-mode operation in a narrow beam-pattern poses unconventional challenges due to the subwavelength dimensions of the emitting aperture. Also, they have developed new techniques in waveguide engineering to overcome those challenges, and have demonstrated a unique method to tune the resonant-cavity mode of metal-metal terahertz "wire lasers" for realizing the continuous tuning over a range of 137 GHz for a 3.8-THz QC.

Terahertz quantum cascade lasers are quite compact, electrically pumped semiconductor laser sources, which are capable of producing tens of milliwatts of power in CW mode of operation. Barbieri et al. [16] have demonstrated that these devices can be operated in a regime of active mode-locking by modulating their bias current with a radiofrequency synthesizer, and have shown that the detection of the emitted pulse train can be made possible by phase-locking the quantum cascade laser repetition rate and carrier frequency to a harmonic of the repetition rate of a mode-locked femtosecond fibre laser. It has been emphasized that this technique allows (i) coherent sampling of the terahertz electric field, showing that the terahertz pulses are transform-limited; and (ii) control of the carrier-envelope phase shift of the quantum cascade laser.

It is now established that the Mid-infrared quantum cascade lasers are semiconductor injection lasers whose active core implements a multiple-quantum-well structure, in which by relying on a designed staircase of intersubband transitions, it is possible to have free choice of emission wavelength in contrast with diode lasers, and also a low transparency point, which is similar to a classical, atomic four-level laser system. Yu et al. [17] have emphasized that (i) in recent years, this design flexibility has expanded the achievable wavelength range of quantum cascade lasers to ~3–25 μm and the terahertz regime, and has also provided great improvements in overall performance; and (ii) QCLs are rapidly becoming practical mid-infrared sources for a variety of applications such as trace-chemical sensing, health monitoring and infrared countermeasures. Yu et al. [17] have reviewed the two major areas of recent improvement: power and power efficiency, and spectral performance in the QCLs.

Gao et al. [18] have discussed recent developments in terahertz quantum cascade lasers for practical applications. It is now well established that Terahertz (THz) quantum cascade laser (QCL) is an electrically pumped unipolar photonic device in which light emission takes place due to electronic transitions between subbands formed by multiple strongly coupled quantum wells, and is arguably the most promising solid-state source to realize various THz applications, including high-resolution spectroscopy, real-time imaging, chemical and biological sensing, and high-speed wireless communication. As stated by them, till today,THz QCLs have covered emitting frequency from 1.2 to 5.4 THz when operating without the assistance of an external magnetic field; and the highest output power is in hundreds milliwatt and watt levels continuous-mode and pulsed-mode operations, respectively. Though THz QCL-based local oscillators have been implemented in astronomy for the identification of atoms and ions , yet there are also limitations, including under room-temperature operation, large divergent beam, narrow single-mode frequency tuning range, incomplete polarization control, and narrow-range frequency comb operation that hinder the widespread applications of THz QCLs, inspite of continuous efforts having been made to improve those THz QCL properties in order to satisfy the requirements of different THz applications. Gao et al. [18] have provided a report , in which the key output characteristic developments of THz QCLs in the past few years, and aim to speed up THz QCLs toward practical applications have been discussed.

Having various advantages of high optical power, high efficiency and design flexibility in a compact size, quantum cascade lasers (QCLs) have proved to be excellent mid-to-far infrared laser sources for gas sensing, infrared spectroscopic, medical diagnosis, and defence applications. Also, Metalorganic chemical vapor deposition (MOCVD) has been found to be an important technology for growing high quality semiconductor materials, and has achieved great success in the semiconductor industry due to its advantages of high efficiency, short maintenance cycles, and high stability and repeatability. In addition, the utilization of MOCVD for the growth of QCL materials holds a significant meaning for promoting the large batch production and industrial application of QCL devices. Sun et al. [19] have summarized the recent progress of QCLs grown by MOCVD.It has been pointed out that mainly material quality and the structure design together determine the device performance. In addition, they have discussed the Research progress on the performance improvement of MOCVD-grown QCLs based on the optimization of material quality and active region structure. Slivken and Razeghi [20] have reported the room temperature demonstration of a high power, continuous wave, LWIR quantum cascade laser grown directly on a Si substrate by processing a new wafer, based on a high efficiency, strain-balanced laser core into a lateral injection buried heterostructure laser geometry. Also, they have demonstrated (i) a pulsed efficiency of 11.1% at room temperature, with an emission wavelength of $8.35~\mu \text{m}$, and (ii) with low fidelity, epilayer-up packaging, CW emission up to 343 K, with a maximum output power of > 0.7 W near room temperature.

Kacmoli and Gmachl [21] have studied Quantum cascade disk and ring lasers. (QCLs) have proved to be a prominent semiconductor laser source operating in the mid-infrared and terahertz regimes. So, as in case of other semiconductor lasers, QCLs usually monolithically integrate the active gain material and the resonator. Therefore, over nearly 3 decades of QCL development, resonator geometries have developed alongside active region designs. Interestingly, disk and ring geometries, have long been recognized for their unique attributes, which have contributed to the demonstration of ultra-small cavities as well as surface emission from QCLs. Ring geometries have recently witnessed a resurgence as promising platforms for frequency comb and soliton generation as well as mid-infrared photonic integration. Kacmoli and Gmachl [21] have described the attributes that make ring and disk QCLs unique by discussing key demonstrations, and presented recent results, which indicate that these devices are poised to become building blocks of highly integrated, next-generation spectrometers operating in the mid-infrared. In addition, they have discussed promising avenues for future research centered around monolithic ring and disk-type QCLs in applications ranging from gas sensing and spectroscopy to quantum optics and non-Hermitian photonics. Thus, it is clear that the field of QCLs is expanding, and finding very interesting new applications.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. Nand Kishore Garg, Founder Chairman, Maharaja Agrasen Institute of Technology, GGSIP University, Delhi for providing the facilities for carrying out this research work, and also for his moral support. The authors are thankful to Dr. M. L. Goyal, Vice Chairman (Academic) and Dr. Satvir Deswal, Dean (Academic) for their encouragement.The author is grateful to the listed researchers and agencies for providing the images. The authors are grateful to the listed researchers and agencies for providing the images.

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