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Semiconductor lasers/Lasers semiconducteurs

Quantum Cascade Lasers: the quantum technology for semiconductor lasers in the mid-far-infrared

Carlo Sirtori [a,b,*], Julien Nagle [b]

[a] *Matériaux et phénomènes quantique, Université Denis Diderot, Paris 7, 75251 Paris cedex 05, France*
[b] *THALES research & technology, 91404 Orsay, France*

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Abstract

The quantum cascade laser is a new light source based on resonant tunnelling and optical transitions between quantised conduction band states. In these semiconductor devices the principles of operation arise from the quantum engineering of electronic energy levels and tailoring of their wavefunctions. In recent years the performance of these devices has improved markedly and this semiconductor technology is now an attractive choice for the fabrication of mid-far infrared lasers in a very wide spectral range (3–80 µm). At present, quantum cascade lasers are capable of continuous-wave room temperature operation and can deliver 200–300 mW of average power (at $\lambda \sim 9$ µm) operating on a Peltier cooler. ***To cite this article: C. Sirtori, J. Nagle, C. R. Physique 4 (2003).***

Résumé

Lasers à cascade quantique : la technologie quantique des lasers à semiconducteurs dans le moyen et lointain infrarouge. Le laser à cascade quantique est une nouvelle source de lumière cohérente exploitant l'effet tunnel résonant et les transitions optiques entre états quantifiés de la bande de conduction. Dans ces dispositifs semiconducteurs, les principes de fonctionnement sont basés sur l'ingénierie quantique des niveaux d'énergie électroniques et sur la mise en forme de leurs fonctions d'onde. Les performances de ces composants ont rapidement progressé ces dernières années et cette technologie représente désormais une solution de choix pour la fabrication de lasers dans le moyen et lointain infrarouge pour un très large domaine spectral (3–80 µm). Aujourd'hui, les lasers à cascade quantique peuvent fonctionner à température ambiante et peuvent fournir 200–300 mW de puissance moyenne (à 9 µm) avec un simple étage de refroidissement Peltier. ***Pour citer cet article : C. Sirtori, J. Nagle, C. R. Physique 4 (2003).***

Keywords: Semiconductor laser; Quantum cascade laser; Mid-infrared; Far-infrared; Quantum engineering; Resonant tunneling; Relaxation time

Mots-clés : Laser semiconducteur ; Laser à cascade quantique ; Infrarouge moyen ; Infrarouge lointain ; Ingénierie quantique ; Effet tunnel résonant ; Temps de relaxation

* Corresponding author.
E-mail addresses: carlo.sirtori@thalesgroup.com (C. Sirtori), julien.nagle@thalesgroup.com (J. Nagle).

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1. Introduction

In this article we review the principal features of quantum cascade (QC) lasers [1–3] and give an overview on the performance which is attainable, at present, with this type of mid-IR semiconductor laser. We first illustrate the fundamentals of QC lasers and the principle of designing an active region. We then discuss the advantage of having this laser technology available on the industrial platform of GaAs [4] and InP, and then we will introduce the other heterostructures where the QC concepts has been implemented, and finally evaluate the merit of developing QC lasers in less conventional material systems [5,6]. In the following section we focus on the wavelength range of operation of QC lasers, highlighting the most recent results achieved in the far infrared, $\lambda \sim 80$ µm [7]. The fourth section is dedicated to an overview of the most relevant results obtained with these mid-infrared lasers in terms of performance and technological achievements. In the last section, before concluding, we suggest what we believe are the most relevant potential applications for this emerging semiconductor laser technology.

2. The fundamentals of quantum cascade lasers

2.1. The main characteristics of QC lasers

Semiconductor diode lasers, including quantum well lasers, rely on transitions between energy bands in which conduction electrons and valence band holes, injected into the active layer through a forward-biased p–n junction, radiatively recombine across the material bandgap. The latter essentially determines the emission wavelength of the device. In contrast, in QC lasers the laser transitions occur between conduction band states (subbands) arising from size quantisation in a semiconductor heterostructure (Fig. 1). These transitions are commonly denoted as intersubband transitions. Their initial and final states are in the conduction band and therefore have the same curvature in reciprocal space (i.e., the same mass). As a consequence, only one type of carrier – typically electrons – is present in these devices (unipolar devices) [8]. This is a very important property which strongly differentiates QC from diode lasers. The other fundamental feature of QC lasers is the multistage cascade scheme, where electrons are recycled from period to period, contributing each time to the gain and the photon emission. Thus, each electron injected above threshold can generate, in principle, N_p laser photons, where N_p is the number of stages. This leads to a very high quantum efficiency and optical power, both proportional to N_p [8].

2.2. Active region design

The scheme illustrated in Fig. 1(b) is evidently an oversimplification of one stage of a quantum cascade active region. Each stage, a fundamental unit of QC lasers, is normally composed of a sequence of 5 to 8 coupled quantum wells as it is represented in Fig. 2. This complex structure is one of the possible solutions which allows population inversion between two subbands of the conduction band [9]. The main challenge is the extremely short lifetimes τ_i of the excited states, which are typically around 1 ps for vertical transitions if the energy separation between the subbands is about a few (4–5) optical phonon energies ($\hbar\omega_\mathrm{LO} \sim 36$ meV in GaAs). This short lifetime is imposed by the electron–phonon interaction which is the dominant energy relaxation mechanism for electrons in the excited subbands. The characteristic time of this interaction is associated to the momentum transfer k that electrons exchange with the lattice and is longer for larger k. Thus the higher the energy separation between the subbands, the longer is their lifetime [10]. When the separation between the subbands is instead close to $\hbar\omega_\mathrm{LO}$, the scattering time is exceptionally short, in the 0.2–0.3 ps range.

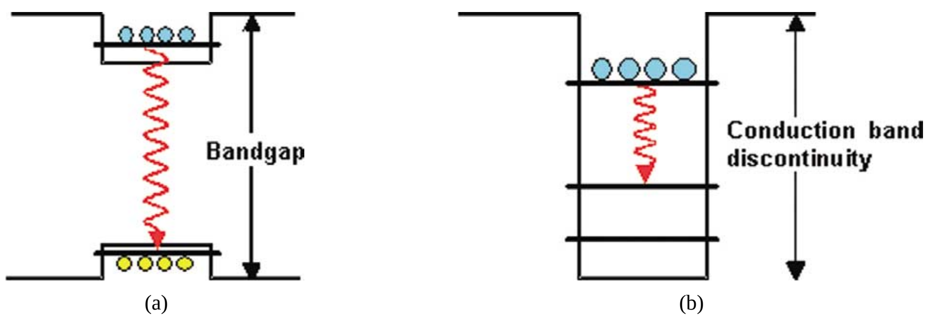

Fig. 1. Different type of optical transitions in semiconductor quantum wells. (a) *interband* transition: electron–hole recombination across the bandgap. (b) *intersubband* transition: transition between two electronic states in the conduction (valence) band.

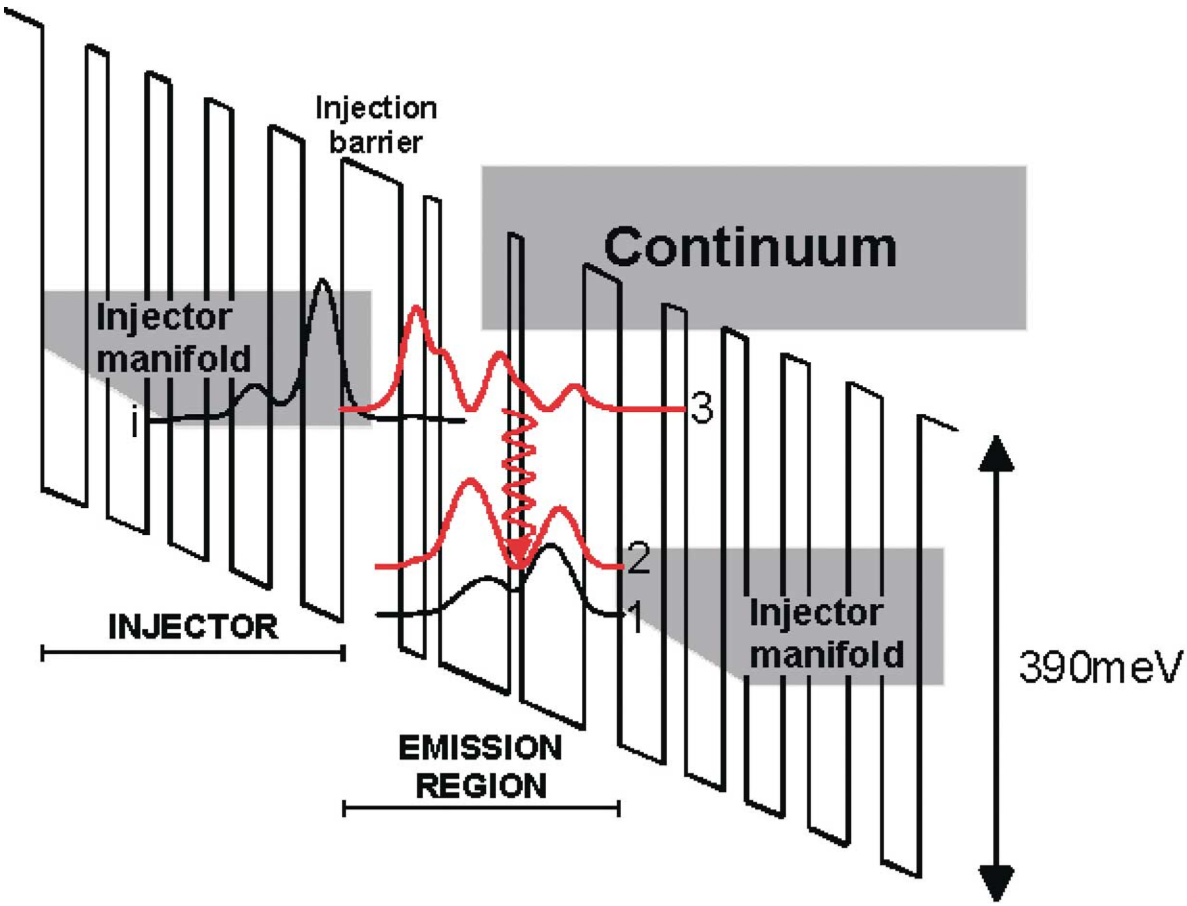

Fig. 2. Schematic conduction band diagram of a portion of the laser heterostructure at the threshold bias. The wavy arrow indicates the transition $3 \to 2$ responsible for the laser action. The solid curves represent the moduli squared of the relevant wavefunctions. The calculated energy level differences are $E_{32} = 134$ meV and $E_{21} = 36$ meV. The grey regions indicate the energy and spatial extension of the manifold and band-like states originating from the injector quantum wells.

Fig. 2 illustrates the conduction band diagram and the corresponding moduli squared of the relevant wavefunctions of a portion of the 36-period section of a GaAs/$Al_{0.45}Ga_{0.55}As$ quantum cascade laser [11] under an applied electric field $\sim$48 kV/cm corresponding to the threshold bias condition. Each stage of the active region can be schematically divided in two parts: (i) the *emission region,* where the radiative recombination takes place; and (ii) the *injector,* an electron reservoir where carriers thermalise before they are re-injected in the next adjacent emission region. The two parts are connected by the injection barrier, which electrons traverse while tunnelling from the ground state of the injector ($n = i$ in Fig. 2) into the $n = 3$ energy level of the emission region [12]. The tunnelling rate across the injection barrier is much faster than the lifetime $\tau_3 = 1$ ps (where $\tau_3^{-1} = \tau_{32}^{-1} + \tau_{31}^{-1}$). This ensures thermal equilibrium between the electron population in the $n = 3$ level and the bottom state of the injector [12]. The calculated energy differences are $E_3 - E_2 = 132$ meV and $E_2 - E_1 = 36$ meV. The coupled well region is essentially a four-level laser system, where population inversion is achieved between the two excited states $n = 3$ and $n = 2$. The intersubband optical-phonon-limited relaxation time, τ_{32}, between these states is estimated to be 2 ps at the threshold bias; τ_{32} is relatively long since the electron–optical phonon interaction is, in this case, between two states of reduced spatial overlap and accompanied by a large momentum transfer due to the fact that the intersubband energy separation is only a few times the LO-phonon energy. Thus the population inversion condition $\tau_{32} - \tau_2 > 0$ is easily verified because the lower state ($n = 2$) empties with a relaxation time estimated around 0.3 ps, due to the optical phonon resonance emission with the state $n = 1$.

3. QC lasers based on different material systems

There are no substantial differences in the conception of QC lasers using one material or another, as the overall principles accounting for population inversion are basically controlled by the same physical effects.

The first demonstration of a QC laser was achieved in 1994 at AT&T (now Lucent Technologies) Bell Laboratories by Faist et al. [1] using $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ grown lattice matched on InP. It took about four years before QC lasers could be reproduced in a different heterostructure. This was demonstrated in 1998 by a group of researchers at Thales R&T (formerly Thomson-CSF Laboratoire Central de Recherches) using $GaAs/Al_{0.33}Ga_{0.67}As$ [4]. The realisation of QC lasers using (Al)GaAs based heterostructures, the most widespread and developed among compound semiconductors, conferred an additional technological value to these devices.

At present GaAs QC lasers [13] have not yet reached the performance of the InP based devices, but have already shone light on some advantages which are attainable with a GaAs based technology. Among those we recall the utilisation of very mature processing techniques and the high purity of the material which allows the realisation of low loss waveguides. This is very relevant, especially in the far infrared where QC lasers have been obtained only in GaAs based heterostructures. However, practically all of the results relevant for technological applications, presented in Section 5, are referred to InP based laser [9,14].

Apart from GaAs and InP based heterostructures, other material systems have also attracted a lot of interest for the realisation of QC lasers. These investigations are particularly advanced for two heterostructures: Si/SiGe and InAs/AlSb grown lattice compensated on GaSb. In these materials, although laser action has not yet been demonstrated, QC active regions have been already realised and intersubband electroluminescence observed [5,6].

The realisation of QC lasers in Si/SiGe would represent a major breakthrough simply because it would represent the first laser based on Si. In this material system the intersubband transitions occur in the valence band, which is a complication from the point of view of the theoretical description. Moreover, the presence of the different holes with different dispersion curves (heavy, light and split-off), increases enormously the number of subbands and makes more difficult their energy separation. Even if preliminary, the recent results on electroluminescence [5] represent in our opinion the closest ever obtained to the demonstration of a Si based semiconductor laser.

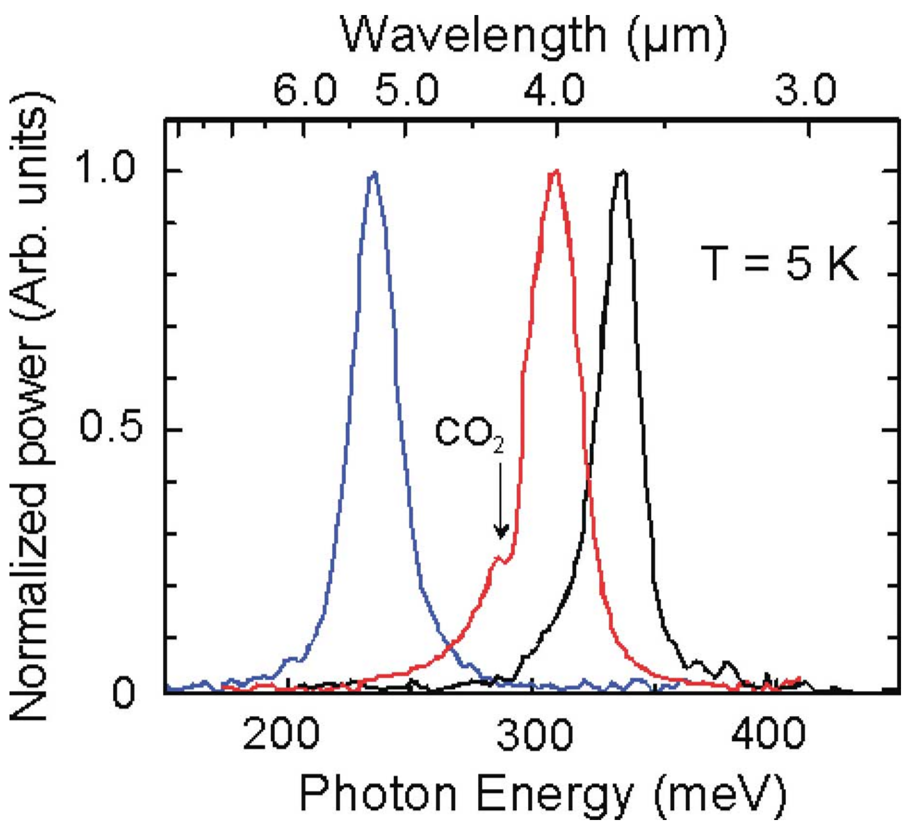

Fig. 3. Electroluminescence spectra of three QC structures based on InAs/AlSb quantum wells designed for emission wavelengths at 3.6, 4.2 and 5.3 µm. The measured peaks are at 3.7, 4.0 and 5.2 µm respectively, in very good agreement with the desired values. This proves the high level of control that has been obtained in this less conventional heterostructure. The arrow indicates the CO_2 absorption line (after [6]; originally published by the American Institute of Physics).

The main factor which limits the lowest wavelength possible for a QC laser is the height of the conduction band offset (ΔE_C) between the heterostructure materials. To this end, InAs/AlSb quantum wells, which have direct band discontinuity of the order of 2 eV, are very good candidates to design lasers around 4 μm wavelength ($E_{\text{photon}\,@4\,\mu\text{m}} = 0.31$ eV). In Fig. 3 we report the electroluminescence spectra from different quantum cascade structures in the 3–5 μm wavelength. Unfortunately the design of the waveguide in this material system still poses some problems and has prevented until now the realisation of the first QC laser based on III–V Sb compounds. The major inconvenience has been found in the realisation of cladding layers (layers with lower refractive index than that of the active region) with sufficient refractive index contrast, low absorption at the lasing wavelength and good electrical properties.

4. Wavelength agility: 3.4–80 μm

Probably the most important consequence of a laser based on intersubband transitions is that the emission wavelength does not depend on the band gap of constituent materials, but can be tuned by tailoring the thickness of the quantum wells. As it has been explained before, the highest achievable photon energy is ultimately set by the conduction-band discontinuity, ΔE_C, of the heterostructure, while on the long wavelength side there are no fundamental limits preventing the fabrication of QC lasers emitting in the far infrared. This can be guessed from the scheme in Fig. 4.

At present QC lasers have been demonstrated in a very wide wavelength range from 3.4 to 80 μm [7,15,16]. The spectra covered by the devices based on AlInAs/GaInAs grown on InP go from 3.4 to 24 μm, whereas lasers fabricated using GaAs/AlGaAs range from 8 μm down to the THz region at 80 μm (3.5 THz). From these results, it appears that the two material systems fit better different parts of the electromagnetic spectrum. InP based lasers extend towards the short wavelength side, because of the higher conduction band discontinuity of AlInAs/GaInAs especially when the materials are strain compensated. In this case ΔE_C can reach 700 meV [16] and therefore easily allows the conception and design of lasers with wavelength around 4–5 μm. For the devices based on GaAs the highest effective discontinuity of the GaAs/AlGaAs heterostructure is limited to $\sim$400 meV. This is imposed by the band structure of the AlGaAs which for a concentration higher than 45%, gets its conduction band minima in the X valley. On the long wavelength side GaAs becomes more performing than InP, fundamentally for reasons of material purity, which increase the mobility and the conductivity of the semiconductor at low temperature and guarantee lower waveguide losses.

It is important to point out that the highest photon energy attainable, i.e., shortest wavelength, is always only a fraction of the conduction band discontinuity. In general one can state that $E_{\text{Photon}}^{\max} \sim \Delta E_C/2$. This can be understood by making the following observation (see also Figs. 1 and 2): the laser transition takes place between two excited states and therefore part of ΔE_C is committed to the zero point energy, for the confinement of the ground state, and to the energy separation E_{12}. Moreover the excited state of the laser transition ($n = 3$) has to be sufficiently deep inside the quantum wells in order to avoid electron injection directly into the continuum of states located above the $n = 3$ state. Otherwise the coupling with the continuum opens a parasitic current path which strongly decreases laser performance. Experimentally it has been observed that for $E_{\text{Photon}}^{\max} > \Delta E_C/2$ the laser performance strongly degrades especially for what concerns the maximum temperature of operation [13]. Obviously, this is not strictly valid, but it can be remembered as a good rule of thumb to immediately identify the shortest wavelength for a high performance laser, in a given material system.

In Fig. 5 the maximum operating temperature of quantum cascade lasers is reported as a function of the emission wavelength. The temperature of operation gives a direct indication of the level of maturity and the degree of performance of the laser. It is remarkable that in both material systems the wavelength of operation extends to approximately one order of magnitude between

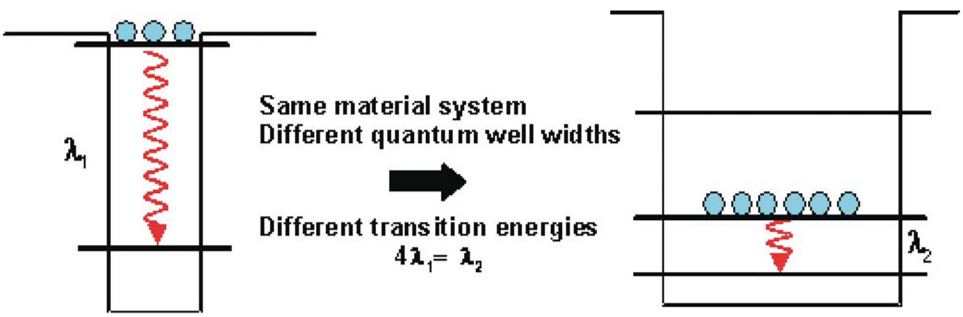

Fig. 4. Intersubband transitions depend primarily on the width of the quantum well and not on the constituent materials of the heterostructure. The highest photon energy is limited by the conduction band discontinuity, while on the low energy side the limit is ultimately imposed by broadening of the quantised levels.

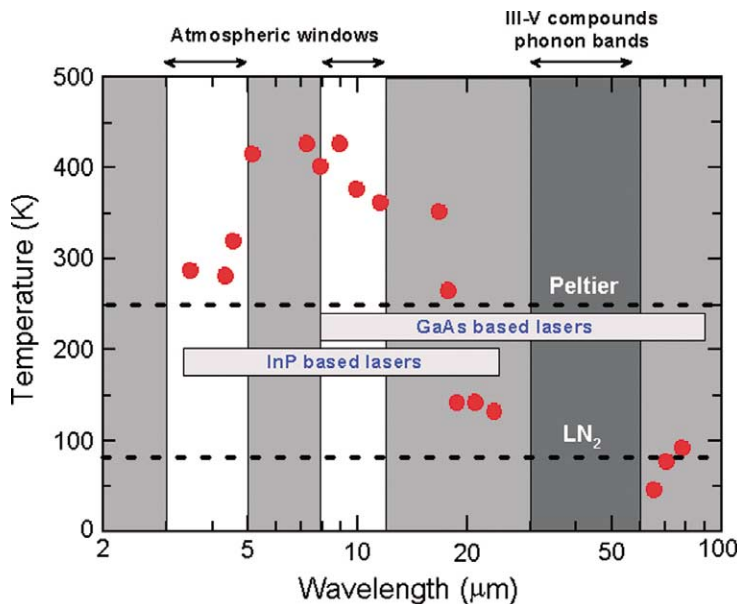

Fig. 5. Maximum operating temperature of quantum cascade lasers as a function of the wavelength. Note that the two material systems where QC are produced do not share the same wavelength range.

the shortest and longest wavelength. If we make a comparison in the frequency domain of interband laser diodes (visible – near infrared) this would be equivalent to a material system capable to produce devices with wavelength emission from 200 nm up to 2 µm!

5. QC laser performances

In the 3.5–100 µm wavelength range, the quantum cascade laser is now outperforming all other semiconductor laser technologies based on current injection. Room temperature operation in pulsed mode has been achieved on a very wide spectral range, from 4 to 16 µm, and peak power in the order of 1 W is routinely obtained [13,17]. Continuous wave (cw) operation up to room temperature has been recently demonstrated at ∼9 µm with an optical power of 10 mW (Fig. 6) [18]. This is the most important technological result that has been demonstrated for QC lasers and opens the avenue for new important applications, such as wireless communications and very high performance optical sensors, based on mid-infrared radiation [9, 14,19]. However, room temperature cw operation is still one of the major challenges for QC laser, due to the very high threshold power densities that generate a strong self heating of the devices. If we look at the numbers we see that at 300 K the best lasers reach threshold at current densities of the order of 3 $\mathrm{kA/cm^2}$. This would represent reasonable injected power for laser diodes, where the voltage is typically of the order of the band gap. However, in QC lasers, due to the cascade scheme, the voltage is a function of the number of periods and it can easily reach several volts. In Fig. 6 we report the light and voltage versus current characteristics (LVI) of the first laser operating at room temperature demonstrated by Beck et al. [18]. We note that the threshold voltage is between 7–8 V. This makes a very high total power density of 25 $\mathrm{kW/cm^2}$. Nevertheless, the total electrical power is kept quite low since a significant reduction in the operating current has been made by a decrease of the active area that has to be pumped. This has been achieved using buried heterostructure lasers with a very narrow lateral width. The reduction of the total area of QC devices, without the addition of extra waveguide losses, is one of the most important issues that is presently under investigation. To this end, two processing technologies are under development: (i) the conventional buried heterostructure used by Beck and co-workers in [18]; and (ii) the selective current channelling by ion implantation recently demonstrated by Sirtori et co-workers [13].

High speed modulation of quantum cascade lasers and mode-locking have been the subject of intense investigations by a group of researchers at Bell Labs led by Capasso [20–22] in the last couple of years. Among all these brilliant experiments, there is one which has particularly attracted our attention: the analysis of the small signal frequency response. The data in Fig. 7 [22] clearly demonstrate the absence of relaxation oscillation resonance for QC lasers. This is a direct experimental evidence that the bandwidth of these lasers will be ultimately determined by the longest of photon lifetime in the cavity and electron

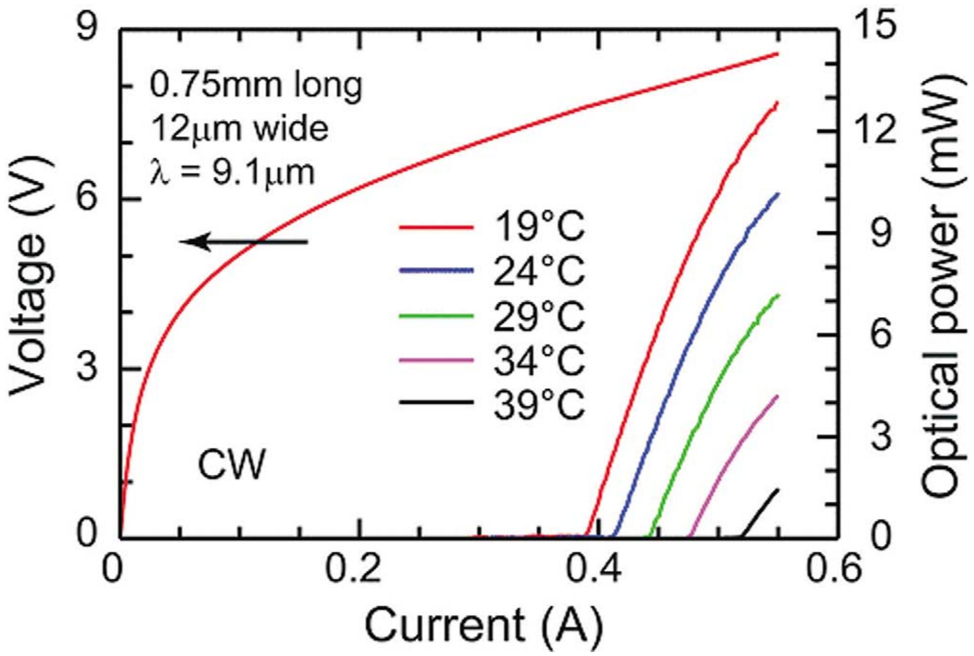

Fig. 6. L–I and V–I characteristics of a buried heterostructure QC laser operating in continuous wave at and above room temperature. Continuous wave power of 17 mW was achieved with this device (after [18]).

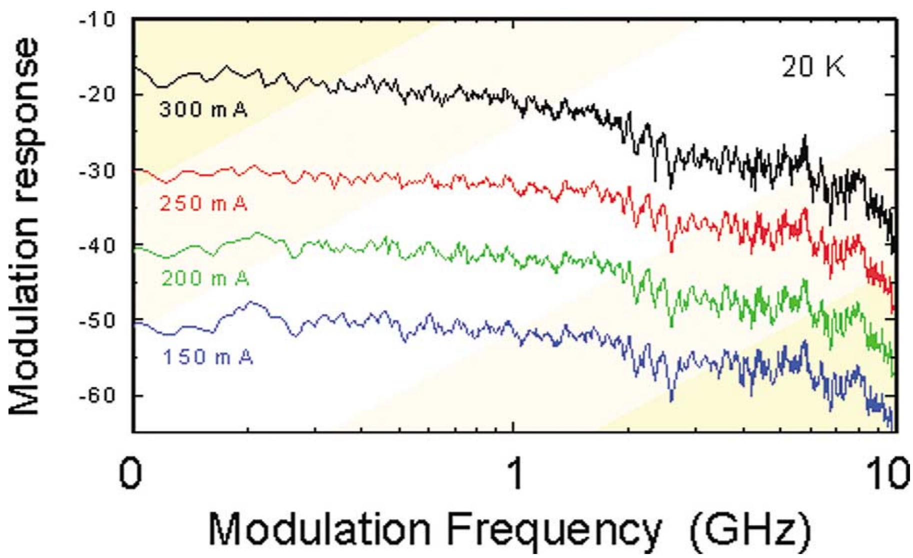

Fig. 7. High-frequency modulation response traces of a 8 μm QC laser at 20 K for different values of the drive current ranging from very near threshold (150 mA), up to one order of magnitude higher photon density (300 mA). These traces were normalised to the experimental frequency response of the receiver and reflect only the modulation response of the QC laser (after [22]).

lifetime in the upper laser state, rather than by the coupled damped oscillations between laser field and carrier population as in conventional diode lasers.

Most of the atmospheric gases have their fundamental roto-vibrational transitions with characteristic frequencies – molecular fingerprints – which are optically active. The corresponding absorption lines lie in the mid-infrared region of the spectrum, covering the 3–15 μm wavelength region. QC lasers are therefore very attractive light sources for molecular spectroscopy, especially when processed as distributed feedback (DFB) lasers for wavelength control and stabilisation [23,24]. In Fig. 8 the

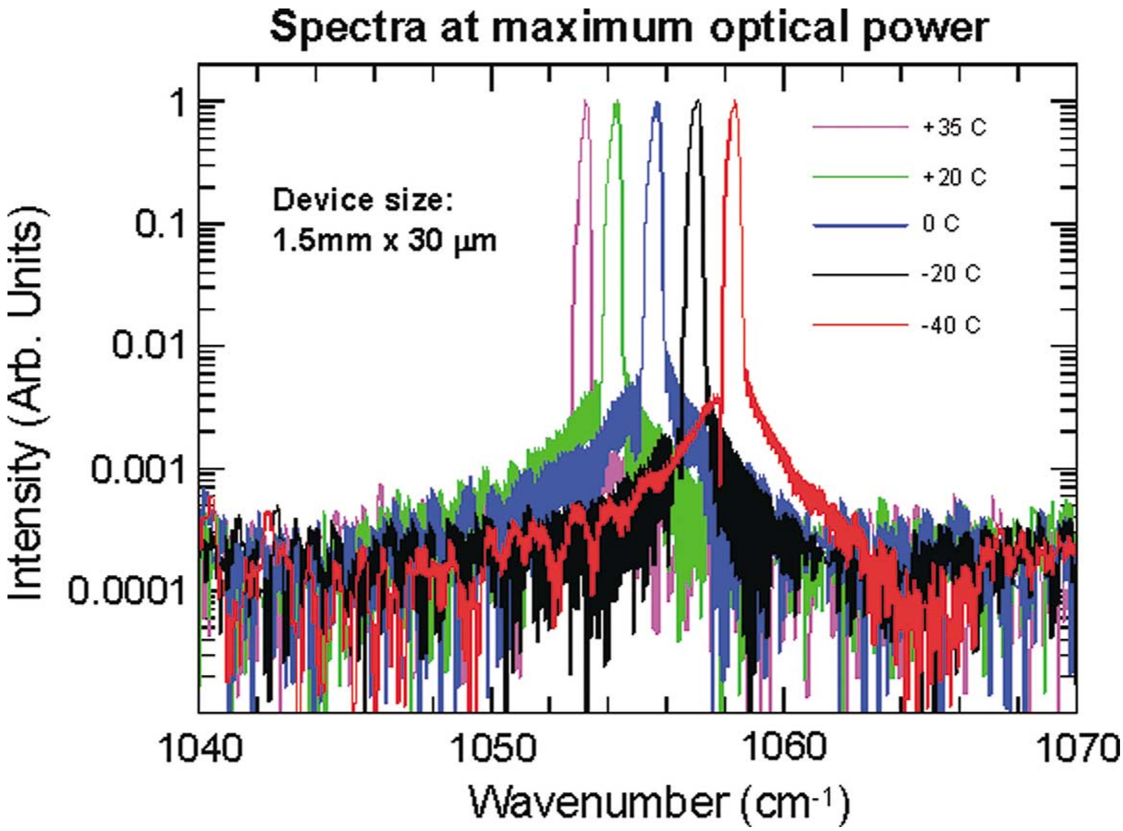

Fig. 8. QC laser spectra of a device processed into DFB. The device operates in pulsed mode (100 ns, 5 kHz) and is mounted on a Peltier element where the temperature is varied between -40 to $+35\,^{\circ}$C. The peak optical power is in excess of 100 mW at all temperatures. Note that in this temperature range the device can be tuned over 5 cm^{-1}.

spectra of GaAs based QC lasers, mounted on a Peltier cooler, are shown. Notice that the emission wavelength varies as function of the temperature, due to the change of the material refractive index. This is a very important parameter that allows the fine tuning of the emission frequency with the molecular resonance. The linewidth of free running DFB lasers has been measured in different experiments and gives a value in the 2–5 MHz range [19,25]. When stabilised by means of an electronic feedback loop, for high stability operation, these devices have shown line with intrinsic width well below 1 kHz [26].

6. Applications and possible industrial exploitation

The success of QC lasers comes for a large part from its potential for wide ranging and important real world applications. In the atmosphere there are two optical transmission windows (3–5 µm and 8–13 µm), where mid infrared optical systems can be used for a wide range of applications. These include military, space and commercial applications [2]. QC lasers can be implemented into systems that, through these windows, can detect many trace gases and vapours with sensitivity up to parts per billion (ppb) today and parts per trillion in the near future [19]. Because of their high power, tuning range and ability to operate at room temperature, QC lasers have attracted a lot of attention for gas sensing applications. As a whole, spectroscopic applications represent the most attractive potential market for QC lasers. They have a very wide range of exploitations: in the following we will give an overview of those we believe have a real potential to become industrial products in the near future:

- *Remote sensing* of chemicals such as toxic gases, vapours emanating from industrial smokestacks, landfills and other hazardous waste site;
- *Point sensors* for (a) evaluation of local concentration of hazardous gases; and vapours (b) short-range sensing for monitoring of automobile emissions on the entrance and ramps of highways, etc.; and (c) combustion and catalytic converter diagnostics;

- *Law enforcement*: (a) detection of explosives and illicit drug production sites; (b) detection of compounds used in illicit chemical processing operations; (c) chemical forensics;
- *Security inspection systems* at airport and other sites with high people concentration for the detection of hidden explosives and illicit drugs;
- *Medical applications* for non invasive diagnostics: (a) breath analysis for early detection of ulcers; (b) ex situ monitoring of the insulin level for the people affected of diabetes;
- *Military applications* for sensors aiming at biological toxins and toxic gases.

Mid–infrared lasers have also other important applications in area such as *wireless communication*, – also defined *Free Space Optics* (FSO) – and collision avoidance radar. In the last couple of years FSO has gained tremendous technological relevance as one of the possible solutions for the 'last mile connectivity'. The latter is one of the main open issues of today's telecom industry which deals with the bottleneck of the data bit-rate when the regional telecom links approach metropolitan areas. For this application QC lasers are perfectly suited devices since the emitted wavelength can be chosen in one of the atmospheric windows and because the longer wavelength is much less sensitive to all scattering phenomena induced by aerosols dispersed in the atmosphere (dust particles, fog droplets, smog, smoke, ...). Martini et al. [27] reported an optical data link using high speed modulated QC lasers up to a frequency of 2 GHz. The same authors have also demonstrated audio/video transmission in a free space optical link based on QC lasers [28]. In this experiment, a television signal was transmitted over a distance of 70 m. While the above reports were about indoor experiments, Stephan Blaser and co-workers [9], at the University of Neuchâtel, have shown an optical data link between two different buildings separated by approximately 350 m.

7. Conclusion

In this review article we have described the basic principles of QC lasers and presented their developments and the possible applications. These mid-infrared lasers are based on quantum structures realised in mature III–V compound semiconductors such as GaAs and InP. This is a great advantage because it allows us to fully exploit the technological progresses that have been achieved on these materials, independently from the research on QC lasers. These devices are a very important breakthrough in the field of optoelectronic research and their application potential is undoubtedly far superior to other nano-structured light sources emitting in the same wavelength range. Several possible developments, with a strong industrial potential, are being pursued, in particular spectroscopic and telecom applications.

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