Rapidly Tunable Quantum Cascade Lasers

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(Invited Paper)

Abstract—Operation principles and designs of rapidly tunable quantum cascade lasers (QCL) were analyzed theoretically and experimentally. Theoretical analysis shows that by adding a special polarization transition with controllable intensity or energy to existing QCL designs, one can achieve emission frequency modulation $\Delta \nu \approx 30$ GHz for the carrier wavelength of 10 $\mu$m, while introducing additional optical losses of not more than 10 cm$^{-1}$ in the laser waveguide. Proof-of-principle electrically tunable QCL demonstrated frequency shift of 4.5 GHz. Rapid and continuous frequency tuning of a single-mode distributed-feedback quantum cascade laser (DFB QCL) by optical generation of electron–hole pairs in the laser waveguide and active area was demonstrated. Application of optimized pumping geometry made possible to achieve continuous tuning of a room-temperature-operated DFB QCL in the range of 0.6 cm$^{-1}$ (20 GHz) using 1.3-$\mu$m telecom diode laser as a pumping source. The wavelength of the optically tunable DFB QCL was modulated at frequencies up to 300 MHz.

Index Terms—Distributed feedback lasers, optical FM communications, quantum cascade lasers, spectroscopy, tunable lasers.

I. INTRODUCTION

MID-IR quantum cascade lasers (QCLs) [1], [2] are currently the only semiconductor lasers that can operate continuous wave (CW) at and above room temperature in the spectral range 4–12 $\mu$m. This spectral range includes two mid-IR atmospheric transparency windows $\lambda = 3–5$ $\mu$m and $\lambda = 8–12$ $\mu$m as well as a “molecular fingerprint” region which contains strong molecular vibrational absorption lines that can be used for chemical detection. Due to the reduction of the Rayleigh scattering at longer wavelengths, $\lambda = 8–12$ $\mu$m QCLs are uniquely suited for compact systems for chemical sensing [2], [3], free-space optical communications [3]–[5], medical diagnostics [6]–[9], remote sensing and LIDAR [10]–[12].

A rapidly tunable single mode QCL could provide a revolutionary enhancement to traditional QCL applications such as free space optical communication systems.

As is well known from radio-electronics, compared to AM transmission, the wideband FM system offers a trade of the bandwidth excess for signal to noise ratio (SNR), thus relaxing the transmitter power requirement. The latter is essential for satellite communications, sensor networks and mobile platforms. The FM advantage is proportional to the squared ratio $(\Delta F/f)^2$ of the range of frequency excursion $\Delta F$ to the signal bandwidth $f$ [13], [14]. In order to maintain the FM signal-to-noise advantage the signal modulation frequency $f$ (exemplarily 1 GHz) must be much lower than the tuning range $\Delta F$ (e.g., 10 GHz) which in turn must be much less than the laser center frequency $\nu$ (which is 120 THz at 2.5 $\mu$m). The condition,

$$f \ll \Delta F \ll \nu$$

(1)

is naturally realized in the optical system. A more stringent condition limits the spectral width $\Delta \nu$ of the laser emission. Any laser is a high-Q resonator in the sense of $\Delta \nu \ll \nu$, but since the linewidth is “inherited” in heterodyne detection, one must ensure it stays well below the tuning range:

$$\Delta \nu \ll \Delta F.$$  

(2)

This is certainly quite feasible with single-mode semiconductor lasers.

The signal bandwidth $f$ is the modulation frequency of the laser wavelength. It determines the optical link bit rate and is limited by the tuning mechanism. The higher tuning speed the more information per unit time can be transmitted. A rapidly and continuously tunable single mode QCL could be a key element for an optical FM data link with SNR improved by orders of magnitude in comparison with the analog one [13].

Another important application area of tunable semiconductor lasers is tunable diode laser absorption spectroscopy (TD-LAS) and tunable heterodyne spectroscopy [15], [16]. Rapid frequency tuning improves a TDLAS sensor performance through enhancement of time resolution and increased sensitivity. A number of frequency scans determined by the Allan variance along with further averaging produces a clearer absorption spectrum, and hence higher SNR. The clearer spectrum is more suitable for quantitative analysis. At these conditions the total averaging time, which determines time resolution of the sensor, is much longer than the scan time. Reduction of the scan time allows enhancement of the sensor’s time resolution which is crucial for in situ chemical sensing. Fast wavelength scan enhances the system’s sensitivity by filtering out rapidly varying non-selective absorption. This is especially important for chemical sensing in a highly turbulent environment.

For both optical FM communication systems and spectroscopy a continuously tunable single mode QCL is required. Continuous tuning of the laser frequency can be done through the control of the effective refractive index of a single mode distributed feedback (DFB) or distributed Bragg reflector (DBR) laser or using an external cavity with a tunable Q-factor [17].

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The emission wavelength (\(\lambda\)) of a QCL with a first-order DFB or a DBR grating of a period \(\Lambda\) is given as [18]:

\[
\lambda \approx 2 \times \Lambda \times n_{\text{eff}}
\]  

(3)

where \(n_{\text{eff}}\) is the effective refractive index of the laser mode. The changes in either \(\Lambda\) or \(n_{\text{eff}}\) lead to the laser wavelength tuning. A tunable distributed-feedback quantum cascade laser (DFB QCL) with a DFB grating produced by the deformation field of a standing sound wave was proposed in [19]. The DFB period \(\Lambda\), hence, the laser wavelength was controlled through the sound wavelength.

One of the most common ways to tune the laser frequency is changing the laser temperature. It can be done directly through the control of the heatsink temperature or by modulation of the pump current [20]. Though the latter way is faster is still too slow to be used for optical FM communications or chemical sensing with high-temporal-resolution (< 1 \(\mu\)s). The maximum rate of temperature tuning of DFB QCLs in this scheme can be estimated from the known frequency chirp of DFB QCLs operating in pulsed mode. Based on the results reported in [21] one can estimate that it takes approximately 140 ns to tune of the emission frequency of a DFB QCL by 30 GHz (1 cm\(^{-1}\)) by ramping the pump current from zero to above a QCL threshold. In reality, the highest practically possible current-tuning speed for room-temperature single-mode CW devices is at least 10 times longer, because high-performance CW DFB QCLs have efficient thermal packaging that prevents excessive heating and the pump current must be modulated within the device operating range rather than from 0 to well above threshold.

An alternative way of laser frequency tuning is the modulation of the effective refractive index of the laser mode through electrical or optical control of electronic properties of the laser material. In this paper we will demonstrate laser frequency tuning based on rapid change of the effective refractive index of the laser mode.

II. ELECTRICAL TUNING OF A SINGLE MODE QCL

Effective refractive index is, generally, contributed by all possible virtual electronic transitions in the laser structure. The contribution of a transition between energy levels \(E_1\) and \(E_2\) to the effective refractive index of a QCL structure can be expressed as [22]:

\[
\Delta n_{\text{eff}}(\omega) \approx \frac{1}{2} \frac{N_e (e^{2}\gamma)}{n_0(\omega) \varepsilon_0 h} \frac{N_e (e^{2}\gamma)}{\left(\omega_{\Delta} - \omega\right)^2 + \gamma^2} \left[(\omega_{\Delta} - \omega) + i\gamma\right],
\]  

(4)

where \(N_e\) is an electron density in the lower level, \(\omega_{\Delta} = (E_2 - E_1)/\hbar, \gamma\) is the transition linewidth, \(n_0(\omega)\) is the refractive index of the laser structure with \(N_e\), \(z_{12}\) is the transition dipole moment. As it follows from the expression (4) the contribution of the polarization transition (PT) to the real part of the effective refractive index is zero when \(\omega = \omega_{\Delta}\) and maximal at \(\omega = \omega_{\Delta} \pm \gamma\). The optical transition of a QCL does not contribute to the effective refractive index at the resonant frequency which is determined by highly symmetrical shape of intersubband gain/absorption spectrum and is typical for intersubband devices. A manifestation of this fact is the low linewidth enhancement factor in the QCL lasers [23], [24]. Incorporation into a QCL structure a special PT whose frequency and intensity can be controlled after the lasing threshold one can continuously tune the QCL generation frequency. Fast electrical modulation of the PT frequency \(\omega_{\Delta}\) [22], electron concentration \(N_e\) [25] at the lower energy level of the PT or the transition matrix element \(z_{12}\) [26] leads to rapid modulation of the laser wavelength.

A tunable QCL laser with PT incorporated in each cascade right before the injection barrier was proposed in [27]. The carrier concentration at the lower level of the PT was controlled through the laser bias current. Application of a thick injection barrier made possible to avoid gain clamping effect on the intensity of PT transition by decoupling the carrier concentration at the lower level of the PT and carrier concentration in the QCL active region [28].

The performance of mid-IR QCLs that integrate an independently-biased “refractive index modulation” (RIM) layer with tunable intersubbands transitions next to the laser active region was investigated theoretically and experimentally in [22]. The layout of the electrically-tunable QCL is shown in Fig. 1(a). The RIM layer is a periodic structure with the period comprising two coupled quantum wells with a diagonal transition shown in Fig. 1(b) and (c).

The transition frequency \(\omega_{\Delta}\) between the ground and the first excited state in the coupled quantum well structure can be
tuned in the range $\Delta \omega_{12}$ by applying bias voltage as shown in Fig. 1(c), which will lead to a change in $n_{\text{eff}}$ of the laser mode and tune the emission frequency according to Eq (3). A similar QCL design approach has been recently used by Teissier et al. [29], [30] for AM modulation of QCLs and an FM modulation of a QCL output has also been observed [29]. However, devices in [29] and [30] are optimized for AM modulation; namely, the intersubband transition energy at zero bias voltage in the RIM layer in these devices is nearly coincident with the laser emission frequency. In contrast, as discussed below, our devices are optimized for FM modulation: the intersubband transition energy in the RIM layer is significantly detuned from the laser emission frequency.

Assuming that $\omega_{12} - \omega \gg \gamma_{12}$, $\Delta \omega_{12}$ and neglecting the optical absorption in the laser waveguide core the amplitude of the RIM in the RIM layer $\delta n_{\text{RIM}}$ and additional optical loss due to the RIM layer $\delta \alpha_{\text{RIM}}$ can be expressed as [22]:

$$\delta n_{\text{RIM}} \approx \Gamma_{\text{RIM}} \frac{N_e (e \varepsilon_{12})^2 \Delta \omega_{12}}{2 n_0 (\omega) e_0 \hbar (\omega_{12} - \omega)^2},$$

$$\delta \alpha_{\text{RIM}} \approx \Gamma_{\text{RIM}} \frac{\omega}{c} \frac{N_e (e \varepsilon_{12})^2 \gamma_{12}}{n_0 (\omega) e_0 \hbar (\omega_{12} - \omega)^2},$$

where $\Gamma_{\text{RIM}}$ is the modal overlap with the RIM layer. From Eqs. (5), (6) we see that, within the approximations used, optical losses and RIM amplitude are related as [22]:

$$\frac{\delta n_{\text{RIM}}}{\delta \alpha_{\text{RIM}}} = \frac{c \Delta \omega_{12}}{\omega 2 \gamma_{12}},$$

where $\omega$ is the laser operating frequency.

Equation (7) determines fundamental limits of frequency tuning using DFB QCLs with a RIM layer. Assuming $\omega = 1.88 \times 10^4 \text{s}^{-1}$ (corresponding to $\lambda = 10 \mu m$), $(h/\gamma_{12} \approx 13 \text{ meV})$ [14], [15], $\delta \alpha_{\text{RIM}} = 10 \text{ cm}^{-1}$, and a value of $\Delta \omega_{12} \approx 50 \text{ meV}$, one can obtain from Eq. (7) that it is possible to achieve the effective refractive index tuning by $\delta n_{\text{RIM}} = 3.0 \times 10^{-3}$. Given a typical effective refractive index $n_0 \approx 3.2$, this value of $\delta n_{\text{RIM}}$ translates into frequency tuning of $\Delta \nu \approx 30 \text{ GHz}$ for $\lambda \approx 10 \mu m$ QCLs according to Eq. (3).

A proof-of-principle $\text{Al}_{0.45}\text{In}_{0.55}\text{As/Ga}_{0.47}\text{In}_{0.53}\text{As}$ FM QCLs based RIM concept were grown by molecular beam epitaxy on an InP substrate n-doped to $1-3 \times 10^{18} \text{ cm}^{-3}$. The growth started with 2.0 $\mu m$-thick InP waveguide cladding layer n-doped to $4 \times 10^{16} \text{ cm}^{-3}$, followed by a 19-times repetition of the RIM structure shown in Fig. 1(b) and (c), a 100 nm-thick InP current extraction and etch-stop layer n-doped to $5 \times 10^{17} \text{ cm}^{-3}$, a 30-stage active region based on the double-phonon depopulation concept [31] designed for operation at $\lambda \approx 9.6 \mu m$, a 400 nm-thick $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ layer n-doped to $4 \times 10^{16} \text{ cm}^{-3}$, and a 3.5 $\mu m$-thick waveguide cladding layer of InP n-doped to $4 \times 10^{16} \text{ cm}^{-3}$. The growth was concluded by a 0.5 $\mu m$-thick layer of InP n-doped to $5 \times 10^{18} \text{ cm}^{-3}$.

Devices were processed as ridge-waveguide lasers, cleaved into approximately 3 mm-long laser bars, mounted, and wire bonded, following the scheme shown in Fig. 1(a). The electron micrograph image of a processed device is shown in Fig. 2(a). For testing, devices were operated in pulsed mode with 50–200 ns current pulses at 50–200 kHz repetition frequency. The current–voltage and light output-current characteristics of a 3 mm-long 10 $\mu m$-wide ridge device with zero bias applied to the RIM section are shown in Fig. 2(b). The emission spectrum of this laser at $T = 80 \text{ K}$ is shown in Fig. 2(c). The devices were Fabry–Perot lasers and did not contain DFB gratings. However, several devices did produce single-peak emission spectrum, as shown in Fig. 2(c) for a wide range of pumping currents.

Laser spectra obtained at $T = 80 \text{ K}$ at different RIM bias voltages are shown in Fig. 3(a). A clear shift in the QCL emission frequency as a function of the RIM voltage was observed. Experimental and theoretical dependencies of the frequency shift of the laser emission and threshold current density change as functions of the RIM bias voltage are presented in Fig. 3(b) and (c). Theoretical dependence of the threshold current change (see Fig. 3(c)) obtained in the assumption that threshold current is linearly proportional to the total loss in the laser cavity, $\alpha_{\text{tot}} = \alpha_m + \alpha_{w/g}$, where $\alpha_m = 4 \text{ cm}^{-1}$ is the mirror loss for a 3 mm-long device and $\alpha_{w/g}$ is the waveguide loss. The experimental data is in good agreement with the theoretical prediction.

In a DFB QCL the lasing wavelength is determined by the parameters of the grating and can be detuned from the gain maximum. Stable DFB operation was demonstrated at sufficient frequency difference between the laser generation wavelength and the gain maximum [32]. This makes possible to use the optical transition of a QCL as a PT. The advantages of this approach are the absence of the additional optical loss due to PT and simple device package since the laser wavelength tuning is
done by variation of the bias current and no additional electrode is needed. The main technical challenge for implementing this approach is that the requirement of the optical gain pinning after the threshold effectively “freezes” the carrier concentration in the laser active region and the voltage drop across the optical quantum wells. In other words the “differential resistance” of the active area after the threshold becomes close to zero [33] and the additional voltage drops on the injectors eventually leading to the Stark breakup. This leads to reduced Stark tunability even if the voltage drop across the laser is controlled [26], [28], [34].

A possible way to solve this problem is to introduce a thick tunnel barrier which reduces the coupling between the upper level of the lasing transition and the injector states. As the injection current increases above threshold, electrons redistribute in the injector to screen the external electric field and accumulate in the superlattice injector wells adjacent to the tunnel barrier. Their concentration determines the tunneling rate into upper laser energy level. As the injection current increases, the carrier concentration near the injection barrier and, hence, the electric field across the active area increases as well. The energies of the states in the active area and the emission wavelength $\lambda$ become dependent on the bias current. The concentration of the accumulated carriers depends on the ratio between the characteristic time associated with the tunneling through the injection barrier and the lifetime of the upper lasing state. This “tunnel-limited injection” approach was successfully demonstrated in Interband Cascade lasers [28], where $\sim 120$ cm$^{-1}$ electrical tuning of the lasing wavelength was achieved.

An example of an electrically tunable QCL structure is shown in Fig. 4(a). To increase electric field tunability a QCL active region is made “diagonal” with spatially separated centers of electron wavefunctions for the upper and lower laser states [34], [35]. Two-phonon depopulation scheme is applied to produce high performance devices [35].

Fig. 4(b) shows calculated transition energies between laser states in the structure displayed in Fig. 4(a) under different bias fields in the active region. Jumps on the electric field dependence of the optical transition energy are due to anti-crossing between the energy levels of the upper laser state and the injector states. The results shown in Fig. 4(b) indicate that one can Stark-tune the laser transition energy by over 15 meV through varying the electric field in the active region from 30 to 50 kV/cm. This shift is comparable to a typical gain linewidth of approximately 25 meV full width at half maximum of a mid-infrared QCL at 300 K [31].

To estimate the dependence of electric field $F$ in a part of a QCL structure where laser states are on a current density through the laser structure, one needs to calculate the amount of charge accumulated in the “charge accumulation” injector state (blue line in Fig. 5) at different current densities. According to Kazarinov and Suris expression for tunneling transport [36], [37]

$$J = eN \frac{2\hbar^2 \tau_p}{1 + \frac{\delta^2 \tau_p^2}{\mathcal{J}^2 \tau_p \tau_u}},$$

(8)

where $2\hbar \Omega$ is the energy splitting between the upper laser state and the adjacent injector state (upper red and blue curves in Fig. 4(a), respectively), $N$ is 2-D electron concentration in the injector state, $\tau_u$ is the lifetime of the upper laser state, $\tau_p$ is the relaxation time of electron in-plane momentum, and $\delta$ is the detuning of the upper laser and injector states:

$$\hbar \delta \approx e \lambda \Delta F; \quad \Delta F = F - F_{res}.$$
Here $F$ is the electric field in the active region, $a \approx 10$ nm is the effective distance between resonantly coupled injector state and upper lasing state (bold blue and upper red curves in Fig. 4(a), respectively), $F_{\text{res}}$ is the electric field at which the injector state and the upper lasing state have same energy. In the first approximation it is assumed that in all voltage range of the laser tuning the effective transport time does not depend on voltage. This approximation is justified as long as $|\delta \tau_p| \leq 1$ which, for $\tau_p = 0.04$ ps [38], means that $\Delta F < 16$ kV/cm.

In Eq. (8) 2-D electron concentration in the injector state [38] instead of the average electron concentration in the active area was used. This modification of the original expression by Kazarinov and Suris takes into account possibility of charge redistribution among the injector states as the bias current is changed. Near the resonance the expression (8) can be rewritten as

$$N \approx \frac{J}{\epsilon \tau_1},$$

where $\tau_1$ is the effective escape time from the injector level:

$$\frac{1}{\tau_1} = \frac{20^2 \tau_p}{1 + 40^2 \tau_p \tau_a}.$$  \hfill (11)

Taking $\tau_p$ as 0.04 ps [38], $\tau_a \approx 0.5$ ps [38], [39] and $2\delta \Omega \approx 2 \text{meV}$ for a QCL structure with a 52 Å injector barrier (see Fig. 4(a)), one can obtain $\tau_1 = 6.4$ ps. Increase in the current through the QCL structure at operational bias voltage leads to carrier accumulation in the injector state. This, in turn, leads to increase of the electric field in the active area of the device. One can estimate an additional electric field $\Delta F$ produced in a part of a QCL structure where the upper and lower laser states are by increasing laser current density above threshold as

$$\Delta F \approx \frac{e(N - N_{th})}{\epsilon_0 \epsilon} = \frac{\tau_1}{\epsilon_0 \epsilon} (J - J_{th})$$

where $\epsilon \approx 13$ is a dc dielectric constant of undoped InGaAs and AlInAs, $J$ and $J_{th}$ are current density through the laser, respectively, and $N$ and $N_{th}$ are 2-D electron concentration accumulated in the injector state at current densities $J$ and $J_{th}$, respectively. According to Eq. (10) the electric field in the active area can be increased by $\Delta F \approx 18$ kV/cm by increasing current density through the device from $J_{th}$ to $J_{th} + 3200$ A/cm$^2$ and $\tau_1 \approx 6.4$ ps.

Another approach to electrical control of the laser frequency is to use inject sound cascade laser [40] with diagonal optical transition and low average doping [41]. The laser structure was designed to maintain current through the active area in a wide voltage range. Low doping and gain pinning lead to suppressed screening of the external electric field and Stark shift of the lasing transition energy. A high performance room temperature operated QCL with electrical tuning of the gain in the range of $100 \text{ cm}^{-1}$ was demonstrated [41].

As the electric field across the QCL active area increases, the center of the laser gain spectrum shifts in accordance with a trend shown in Fig. 4(b). The shift in the position of the laser gain will lead to a change of the effective refractive index of a laser mode at a particular frequency. A QCL gain spectrum can be approximated as:

$$G(\omega) = G_0 \cdot \frac{\gamma_{12} \omega}{(\omega_{12}(F) - \omega)^2 + \gamma_{12}^2}$$

where $F$ is electric field and $G_0$ is determined as [42]:

$$G_0 = \frac{J \tau_1 \left(1 - \frac{\tau_p}{\tau_a}\right) N_{p} \Gamma_{e} |z_{12}|^2}{\epsilon_0 \hbar L \rho \rho_{\text{eff}} c}.$$  \hfill (14)

Here $J$ is the current density, $\tau_1$, $\tau_2$ are electron lifetimes in the upper and lower laser states, respectively, $\tau_{12}$ electron transition time between these levels, $N_{p}$ is the number of cascades, $\Gamma_{e}$ is optical confinement factor per cascade, $L_{p}$ is the length of one cascade, $c$ is the speed of light in vacuum and $\rho_{\text{eff}}$ is the effective refractive index of the mode. Strictly speaking, both dipole matrix element and effective refractive index are functions of the electric field. In first approximation we will neglect these dependencies since the expected variation of the effective refractive index is within $10^{-3}$ and, as seen from Fig. 4(b), the average coordinate matrix element is about 1.9 nm and it does not experience strong variations with the electric field.

The contribution of the laser gain to the variation of the effective refractive index at frequency $\omega$ can be estimated as:

$$\delta n_{\text{eff}} \approx \frac{c}{2} \cdot G_0 \cdot \frac{\omega - \omega_{12}(F)}{(\omega_{12}(F) - \omega)^2 + \gamma_{12}^2}.$$  \hfill (15)

After threshold, the laser gain $G$ is pinned at the lasing frequency $\omega_{L}$, which is determined by a DFB grating period and a value of $n_{\text{eff}}$, see Eq. (3). This can be expressed as

$$G(\omega_{L}(F)) = \alpha_{tot}.$$  \hfill (16)

The gain pinning is maintained even at high modulation frequencies due to suppression of relaxation resonance in QCLs [43]. Taking into account expression (15) the variation of the effective refractive index at the lasing frequency can be
written as:

$$\delta n_{\text{eff}}(\omega_L(F)) \approx \frac{c}{2} \cdot \frac{\alpha_{\text{tot}}}{\gamma_2} \cdot \frac{\omega_L(F) - \omega_{\gamma_2}(F)}{\omega_L(F)}.$$

(17)

To solve Eq. (17) we note that the expected tuning range of a DFB laser wavelength (\(\omega_L\)) in our devices is much smaller than the Stark tuning range of the optical gain. We can then replace \(\omega_L(F)\) to a constant \(\omega_{L,0}\) corresponding to the DFB laser emission frequency at laser threshold. Taking \(\alpha_{\text{tot}} = 15 \text{ cm}^{-1}\), \(2\gamma_2 = 30 \text{ meV}\) and using data of the Fig. 4(b) for the laser gain tuning range after threshold we calculate the variation of the effective refractive index as \(\sim 1.2 \times 10^{-3}\) (see Fig. 5). In terms of frequency the tuning range is \(\sim 13.3 \text{ GHz}\). The possibility of using lasing transition as a PT in DFB QCL lasers was indirectly confirmed by the observations in [44] and [45]. The authors demonstrated strong dependence of a linewidth enhancement factor of a DFB QCL on the detuning between the gain maximum and DFB wavelength.

The maximum wavelength of a cascade laser gain can be electrically modulated at frequencies exceeding 1 GHz [46], [47]. Taking into account that a typical linewidth of a DFB QCL is \(\sim 60 \text{ MHz}\) [48], the conditions expressed by Eq. (1) and (2) can be easily fulfilled for electrically tunable QCL.

III. OPTICAL TUNING OF A SINGLE MODE QCL

Optical excitation of electron–hole pairs in a QCL is a direct way to tune the laser wavelength through control over effective refractive index of the laser mode. It combines advantages of continuous single mode tuning and high wavelength modulation speed. Due to unipolar nature of the QCL, generation of electron-hole pairs in the laser’s active area does not contribute directly to the population inversion but has strong effect on the effective refractive index and, hence, according to the Eq. (3), on the spectral position of the laser modes.

Chen et al. [49] demonstrated 0.375 nm wavelength modulation (∼2 GHz frequency modulation) amplitude of a mid-IR QCL operated at 77 K by illuminating the QCL facet by 820 nm emission from a Ti:sapphire laser. The bandwidth of the wavelength modulation was estimated experimentally as 1.67 GHz. To increase both tuning efficiency and pumping uniformity, pumping wavelength of 1064 nm was used in [50]. This wavelength is in the transparency region of InP substrate and InGaAs outer cladding layers of the QCL and is matched well to the absorption edge of the GaInAs inner waveguide cladding and the active region. The optical excitation of electron-hole pairs is achieved through the device illumination along the whole laser waveguide through the substrate for epilayer-side-down mounted devices (see Fig. 6(a) and (b)).

The contribution of photo excited carriers to the effective refractive index can be estimated using Drude model as [51]:

$$\Delta n_{\text{eff}} \approx -n_0 \left( \Gamma_r \frac{\Delta \omega^2_{pr}}{2\omega^2_{pr}} + \Gamma_a \frac{\Delta \omega^2_{pa}}{2\omega^2_{pa}} \right),$$

(18)

where \(\Delta \omega^2_{pr,pa} = \Delta N_{e,a} \epsilon^2 \) is the change in the plasma frequency due to additional carrier concentrations \(\Delta N_{e,a}\) in the waveguide layer and active area, \(\Gamma_a\) and \(\Gamma_r\) are the confinement factors of the laser mode within the active region and cladding layer, respectively, \(\omega\) is the lasing frequency and \(n_0\) is the effective refractive index of the laser mode at zero pumping intensity. Eq. (18) is valid if \(\omega_p \ll \omega\), which is the case of our experiment where \(\omega \approx 2.1 \times 10^{14} \text{ Hz}\) and \(\omega_p \approx 1.39 \times 10^{13} \text{ Hz}\) for the average doping concentration per period of \(N_0 \approx 4 \times 10^{16} \text{ cm}^{-3}\). The effective index variation of \(\Delta n_{\text{eff}} \approx 1.1 \times 10^{-3}\) in a broad area QCL was demonstrated for the pump power of 93 W/cm² [50].

Similar approach was used for optical tuning of a single mode DFB QCL [52]. In this work a 1.3 µm telecom diode laser was used as an optical pumping source for tuning of a room-temperature-operated \(\lambda = 8.52 \mu\text{m}\) DFB QCL (see Fig. 7).

The spectra of interband photoluminescence collected from the facet of the DFB QCL are shown in Fig. 8(a, inset). Two distinct peaks at 6000 cm⁻¹ (744 meV) and 6750 cm⁻¹ (837 meV) correspond to the bandgap of InGaAs waveguide and the effective bandgap of InGaAs/AlGaAsQCL active region.

Laser spectra at different optical pumping powers are shown in Fig. 8(a). As the pumping power increases, the concentration of the photo excited carriers increases as well which, according to the Eq. (18), leads to the reduction of the effective refractive index of the laser mode [6], [8]. So the DFB laser line shifts...
Fig. 9. (a) DFB QCL spectra at different frequencies of the pumping modulation. (b) Dependences of difference in intensities of DFB spectra obtained at dc and modulated pumping (circles) and of the modulation amplitude of the DFB bias voltage on the pumping modulation frequency. The intensity difference $\Delta I_{QCL}$ is taken at 1172.9 cm$^{-1}$ which corresponds to the DFB frequency at dc pumping. [52].

toward higher frequencies (see Eq. (3)). After continuous tuning for about 0.6 cm$^{-1}$ (see Fig. 8(b)), the intensity of the mode drops sharply and another DFB mode appears at the other side of the stop band. The reason for the DFB mode hopping could not be determined unequivocally, but possible candidates include the frequency dependent optical loss, the shift of the stop band with respect to the maximum of the gain spectrum and changes in the reflection phase at the laser facets. Suppression of this mode hopping effect by optimization of the DFB QCL design could further extend the range of continuous tuning.

Modulation bandwidth of the optically tunable DFB QCL was estimated experimentally by monitoring the transformation of the DFB QCL spectrum shape at the increasing intensity modulation frequency of the pumping laser. As long as the modulation period of the optical pumping intensity is longer than the photo excited carrier lifetime, the concentration of photo excited carriers follows the oscillating pumping intensity. Since the measurement setup has a long response time, the measured DFB QCL spectrum represents a single mode QCL emission spectrum averaged over the entire QCL tuning range. As the modulation period of the pumping intensity becomes shorter than the lifetime of the photo excited carriers, the amplitude of the DFB QCL frequency modulation decreases and the measured spectrum becomes that of a DFB QCL with continuous-wave pumping with intensity equals to the average of the modulated pumping intensity (see Fig. 9(a)). The difference between the intensities of the QCL dc and modulated spectra taken at the peak of the dc spectrum is plotted as a function of pumping modulation frequency in Fig. 9(b). Two poles are observed at frequencies of about 30 and 200 MHz. The two poles are attributed to the different carrier lifetimes in the QCL active area and InGaAs cladding layers. At pumping modulation frequencies exceeding 300 MHz the measured QCL spectrum coincides with the one obtained at continuous-wave pumping.

External interband illumination leads to a reduction of the voltage drop across the QCL structure [49]. The dependence of the QCL voltage modulation amplitude on the pump modulation frequency at dc bias current of 400 mA is shown in Fig. 9(b). A single pole was observed at frequencies about 200 MHz. Since most of the QCL bias voltage drops in the active area, only the carriers excited in the active area contribute to the pumping induced voltage modulation. The high frequency pole at 200 MHz can be attributed to the contribution of free carriers in the laser active area, while the 30 MHz pole is the contribution of the photo excited carrier in the waveguide [52].

IV. CONCLUSION

In conclusion, we analyzed theoretically and experimentally the operation principles and designs of rapidly tunable QCL. Theoretical analysis shows that, by adding a special PT with controllable intensity or energy to existing QCL designs, one can achieve emission frequency modulation $\Delta f \approx 30$ GHz for the carrier wavelength of 10 $\mu$m, while introducing additional optical losses of no more than 10 cm$^{-1}$ in the laser waveguide. Proof-of-principle electrically tunable QCL demonstrated frequency shift of 4.5 GHz. Rapid and continuous frequency tuning of a single mode DFB QCL by optical generation of electron–hole pairs in the laser waveguide and active area was demonstrated. Application of optimized pumping geometry made possible to achieve continuous tuning of a room-temperature-operated DFB QCL in the range of 0.6 cm$^{-1}$ (20 GHz) using 1.3 $\mu$m telecom diode laser as a pumping source. The wavelength of the optically tunable DFB QCL was modulated at frequencies up to 300 MHz. The conditions specified in Eq. (2) and (3) are easily fulfilled which makes optically tunable DFB QCL a prospective source for optical FM data links.

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