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<td>Author(s)</td>
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Tunable single-mode slot waveguide quantum cascade lasers

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We report experimental demonstration of tunable, monolithic, single-mode quantum cascade lasers (QCLs) at ~10 μm with a two-section etched slot structure. A single-mode tuning range of 77 cm⁻¹ (785 nm), corresponding to ~7.8% of the relative tuning range, was realized with a ~20 dB side mode suppression ratio within the whole tuning range. Compared with integrated distributed feedback QCLs, our devices have the advantages of easy fabrication and a broader tuning range. Further theoretical analyses and numerical simulations show that it is possible to achieve a broad continuous tuning range by optimizing the slot structures. The proposed slot-waveguide design could provide an alternative but simple approach to the existing tuning schemes for realizing broadly continuous tunable single-mode QCLs. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4875711]

Quantum cascade lasers (QCLs) are unipolar semiconductor lasers, making the optical transitions between the quantized states in the conduction band of semiconductor heterostructure.1,2 Through quantum bandstructure designs, quantized states in the conduction band of semiconductor QCLs and the sample grating distributed feedback QCLs effect tuning mechanism, based on which the coupled-cavity approaches to overcome these limitations is to utilize Vernier-parts of the external cavity QCLs (EC-QCLs) make them an interesting surface acoustic wave (SAW) approach was which greatly complicates the fabrication processes. Recently, the SGDFB-QCLs, on the other hand, require InP regrowth, coupled-cavity QCLs usually exhibit a limited tuning range. Reduced laser linewidth. Even though distributed feedback mode QCLs are more advantageous owing to the much reduced Mie scattering losses.10 The single-mode tuning range of a single DFB QCL is about 10 to 20 wavenumbers. To overcome this limitation, an array of DFB-QCLs with a broad tuning range has been reported,13,14 while this method poses fabrication challenges in ensuring each ridge laser working properly and extra efforts are needed to spatially combine the beams from the array of DFB-QCLs in the far-field.15,16 With the incorporation of QCLs into an external cavity configuration, remarkable tuning ranges have been demonstrated.17,18 However, the mechanical parts of the external cavity QCLs (EC-QCLs) make them vibration sensitive and comparatively expensive. One of the approaches to overcome these limitations is to utilize Vernier-effect tuning mechanism, based on which the coupled-cavity QCLs and the sample grating distributed feedback QCLs (SGDBF-QCLs) were proposed.19–28 Nevertheless, the coupled-cavity QCLs usually exhibit a limited tuning range. The SGDBF-QCLs, on the other hand, require InP regrowth, which greatly complicates the fabrication processes. Recently, an interesting surface acoustic wave (SAW) approach was theoretically proposed and investigated for achieving tunable single-mode emission from QCLs.29,30

In this Letter, we report tunable single-mode two-section QCLs that utilized etched slot structures and a separately electrical pumping scheme to achieve a broad single-mode tuning range. The tuning mechanism can be explained as follows: slots in both front and back sections form two reflectors with the spacing of the reflection spectral peaks determined by the slot spacing. Lasing action occurs when the reflection peaks of the two sections overlap. A slight refractive index change of one section leads to the overlap of another two reflection peaks. As a result, tunable single-mode operation in a wide spectral range can be achieved.31–33

For the present work, a lattice matched 35-periods In0.53Ga0.47As/In0.52Al0.48As active region based on the four well bound-to-continuum design was used with a high doping.34 The waveguide structure is similar to that in Ref. 6. The device processing started with the fabrication of the arrays of slots. A layer of 300-nm-thick Si3N4 was deposited as the hard mask using plasma-enhanced chemical vapor deposition (PECVD). The slot patterns were then defined, by using optical lithography and inductively coupled plasma reactive ion etching (ICP-RIE) reactor with a Cl2/Ar plasma recipe. Laser ridges were then insulated with a 400-nm-thick Si3N4 layer, and Ti/Au metallization bottom contact was evaporated as the top contact with e-beam evaporation. After that, the sample was thinned down to around 200 μm thick and the Ti/Au metallization bottom contact was evaporated. The front and back sections of the slot-QCLs were electrically separated by a 100 μm gap in the Ti/Au top contact layer. The electrical resistance between the two sections of the device was measured to be of ~300Ω. Figure 1 shows the microscopy image of the slot-QCL, with front section length LF = 974 μm, the back section length LB = 1087 μm, and the middle insulation section length...
The zoom-in views show the width of the slot and the slot spacings ($L_f \approx 80 \mu m$ and $L_b \approx 96 \mu m$, where $L_f$ and $L_b$ represent the slot spacings of the front and back sections, respectively) in the two sections. On each section, 11 slots were fabricated to provide a narrow linewidth of the reflection peak while keeping a short device length.

For spacings $L_f \approx 80 \mu m$, and $L_b \approx 96 \mu m$, the spectrum reflection peak spacings are $\approx 18.1 \text{ cm}^{-1}$ and $\approx 15.1 \text{ cm}^{-1}$, respectively.

For spectral characterization, the as-cleaved devices were mounted epi-side up onto the cold finger of a liquid N$_2$ flow cryostat. Spectral characterization was conducted using Fourier transform infrared spectrometer (FTIR) at a resolution of 0.2 cm$^{-1}$ with a calibrated room temperature (RT) HgCdTe detector.

The added slots introduce negligible losses to the laser cavity compared to the Fabry-Perot (FP) ridge lasers due to the small distortion to the laser waveguide structure. To verify this, we measured the threshold current density of a device ($1 \text{ mm } \times 16 \mu m$) with only the front section patterned with slots. The measured value of $6.2 \text{ kA/cm}^2$ is very close to that ($\approx 5.9 \text{ kA/cm}^2$) of the unpatterned device with the same size.

For the slot-QCL, the threshold current density of the front section is measured to be $\approx 10 \text{ kA/cm}^2$ at 300 K when the back section is unbiased. The increased threshold current density is attributed to the strong free carrier absorption in the back section due to the high doping and some current spreading between the two sections. The waveguide loss measured by using the 1/L method results in $\approx 23 \text{ cm}^{-1}$.

To characterize the slot-QCLs, the front section of the device was driven above the threshold by a pulsed current $I_f = 1.2 I_{th}$, where $I_{th}$ is the front section threshold current density when the back section is unbiased. The current pulse duration was 100 ns (short enough to avoid the thermal chirping effect) with a pulse repetition rate of 10 kHz. The back section was driven by using a DC current $I_b$ from 10 to 200 mA. A relatively wide tunable single-mode operation with high side mode suppression ratios (SMSRs) was obtained by simultaneously varying the $I_b$ as well as the heat sink temperature $T$.

For clarity, Figure 2(b) shows selected single-mode spectra of slot-QCLs. Measurements were taken at 100 ns and 10 kHz under pulse operation for the front section. The DC current into the back section varied from 10 mA to 200 mA and the substrate temperature changes from 80 K to 300 K.

(c) Lasing spectrum of a traditional Fabry-Perot laser ($2 \text{ mm } \times 16 \mu m$) biased at 1.2 times of the threshold. The measured temperature is 300 K.

FIG. 2. (a) Single-mode peak evolution with temperature. The legends show the corresponding back section DC currents. The inset shows the current tuning behavior of the device at $T = 297$ K. (b) Selected single-mode spectra of slot-QCLs. Measurements were taken at 100 ns and 10 kHz under pulse operation for the front section. The DC current into the back section varied from 10 mA to 200 mA and the substrate temperature changes from 80 K to 300 K.

Figure 2(b) shows that a total single-mode tuning range of $77 \text{ cm}^{-1}$ (corresponding to 785 nm), which is of 7.8%...
relative tuning range, was realized for slot-QCLs. Continuous tuning range is about 24 cm\(^{-1}\), which accounts for 31% of the whole tuning range. A large continuous tuning range is observed around 970 cm\(^{-1}\), which is due to the flat gain profile and high gain at the centered wavelength as shown in Fig. 2(a) and the inset figure, the temperature tuning coefficients group effective refractive index. The extracted values of flat gain profile and high gain at the centered wavelength as two single-mode emission spectra at ing range is observed around 970 cm\(^{-1}\) for analysis (Fig. 3(a)). The emission spectrum

\[ r_F = r_s \left[ 1 - r_s^{2N} \exp(gNL_f) \exp(-2j\kappa r_{gNL_f}) \right] \]

\[ = \frac{1 - r_s^{2N} \exp(gNL_f) \exp(-2j\kappa r_{gNL_f})}{1 - r_s^{2} \exp(gNL_f) \exp(-2j\kappa r_{gNL_f})} \]

\[ + \frac{r_s^{2N} \exp(g(N - 1) + L_{slf})}{1 - r_s^{2} \exp(g(N - 1) + L_{slf})} \]

\[ \times \exp[-j2(N - 1)\kappa r_{gNL_f} + j\kappa r_{gNL_f}], \] (1a)

\[ r_B = \frac{1 - r_s^{2N} \exp(-\kappa r_{gNL_b}) \exp(-2j\kappa r_{gNL_b})}{1 - r_s^{2} \exp(-\kappa r_{gNL_b}) \exp(-2j\kappa r_{gNL_b})} \]

\[ + \frac{r_s^{2N} \exp(-\kappa r_{gNL_b}) \exp(-2j\kappa r_{gNL_b})}{1 - r_s^{2} \exp(-\kappa r_{gNL_b}) \exp(-2j\kappa r_{gNL_b})} \]

\[ \times \exp[-j2(N - 1)\kappa r_{gNL_b} + j\kappa r_{gNL_b}], \] (1b)

where \( r_s \) and \( t_s \) are the field reflection and transmission coefficients of a single slot, \( r_F \) \( (r_B) \) is the total field reflectivity of the front (back) section, \( g \) is the net modal gain of front section, \( \kappa \) is the loss of the back section, \( \lambda \) is the number of slots, \( k = 2\pi/\lambda \) is the wavenumber in vacuum, \( \lambda \) is the free space wavelength, \( r_F \) is the laser facet field reflection coefficient, and \( L_{slf} \) \( (L_{spb}) \) is the spacing between the laser facet and the adjacent slot in the front (back) section.

In our model, we treat the middle and the back sections as one passive partial reflecting mirror of the whole laser cavity as both sections are biased well below the threshold (no net modal gain). The field reflectivity of this partial reflecting mirror can then be written as \( r_M = r_B \exp(-\kappa r_{slf}) \exp(-2j\kappa r_{slf}), \) where \( \kappa \approx 23 \text{ cm}^{-1} \) is the waveguide loss of the middle section and the back section reflection \( r_M \) can be directly calculated using Eq. (1b). However, calculation of the front section reflection \( r_F \) is not so straightforward. To calculate \( r_F \), as the front section is biased above the threshold, we need to determine the net modal gain \( g \) and the effective length of the front section \( L_{slf} \) (which is also the effective length of the whole laser cavity). The \( g \) can be written as \( g = \frac{1}{2}(r_F r_P) / L_{slf}, \) where \( L_{slf} = \tanh(\kappa/L_P)/2\kappa \) and \( \kappa = v_p/L_P \) is the reflection per unit length of the front section. With the expressions of \( g \) and \( r_P \) as shown in Eq. (1a), a self-consistent approach can then be used to calculate the net modal gain \( g \) and \( r_F \) of the front section.

We used finite-difference time-domain (FDTD) package Lumerical software to determine the \( r_s \) and \( t_s \), by monitoring the optical power of the TM eigenmode at positions just before and after the slot in 3D simulations in which the laser ridge width effects are considered. In the 3D model, the corresponding dielectric constants of different materials in the waveguide structure were calculated using the semi-classical Drude model. The calculated \( r_s \) and \( t_s \) of the slot with a width of 5.5 \( \mu \text{m} \) and a depth of 2.2 \( \mu \text{m} \) are determined to be 0.04 and 0.98. The loss introduced by the slot is \( \approx 2.5 \text{ cm}^{-1} \). The \( r_s \) is set to be 0.54, which is equivalent to the facet power reflectivity of 0.3. The \( L_{slf} \) and \( L_{spb} \) are measured to be \( \approx 160 \mu \text{m} \) and \( \approx 96 \mu \text{m} \) for the front and back sections,
respectively. Using Eqs. (1a) and (1b), the calculated \( r_f \) and \( r_b \) at different characterization conditions are shown in Figs. 3(b)–3(e), where \( g (z_0) \) has been included in the front (back) calculation. It is noted that the reflectivity of the front section in the calculation is greater than unity, which is due to the net modal gain effect in the front section. The measured temperature tuning coefficients \( d_{\text{neff}} / dT = 2.17 \times 10^{-4} \) K\(^{-1}\) and \( d_{\text{neff}} / dI_b = 4 \times 10^{-5} \) mA\(^{-1}\) were utilized in the simulations. It shows that when the temperature changes from 78 K to 158 K, a clear redshift of the reflectivity comb is observed, resulting in the reflectivity peak shifted from 1030 cm\(^{-1}\) (pink solid line in Fig. 3(e)) to 1010 cm\(^{-1}\) (pink solid line in Fig. 3(c)), matching well with Fig. 3(a).

The facet effects on the power reflectivity of one section, e.g., the front section, were also investigated by varying \( L_{pf} \) and \( r_f \). Using Eq. (1a), the corresponding calculated results are shown in Figs. 4(a) and 4(b), where \( g = 0, r_s = 0.04, t_s = 0.97, N = 11, \) and \( L_f = 80 \mu m \). The reflectivity shows strong dependence on \( L_{pf} \) and \( r_f \) with reduced SMSRs. The physics behind is the interference between the light reflected from the laser facet and the slot array. The constructive interference at the designed wavelengths will only occur when \( L_{pf} = nL_f \), where \( n \) is an integer, as shown in Fig. 4(a) with \( L_{pf} = 80 \mu m \). Reducing the facet reflectivity will significantly reduce the effect of laser facet (Fig. 4(b)) and thus lead to an enhanced SMSR and the mode selectivity. Thus, depositing an antireflection (AR) coating on the laser facet would be an effective approach to reduce the laser facet effect.\(^{34}\)

To examine the generation efficiency of Joule heating by the injected current, we estimated the expected temperature variation in the back section. The temperature change in the back section can be written as \( \Delta T = V_b I_b / W_{ac} L_b G_{th} \), where \( V_b \) is the DC voltage applied to back section, \( W_{ac} \) is the width of the active region, and \( G_{th} \) is the active region thermal conductance. For values \( V_b = 1.3 \) V, \( I_b = 40 \) mA, \( W_{ac} = 16 \mu m \), \( L_b = 1.09 \) mm, and \( G_{th} = 45 \) W/K cm,\(^{21}\) the \( \Delta T \) is calculated to be 6.56 K, in agreement with the experimental result of 5.97 K. The difference can be attributed to the current leakage between the two sections.

Compared with other types of coupled-cavity structures,\(^{20–24}\) besides the relatively larger spanning range, our device also possesses a broader continuous tuning range. Although there are still several continuous tuning gaps in the spectra (Fig. 2(b)), this drawback can be overcome if we can vary the local refractive indices of the two sections simultaneously,\(^{28}\) for instance, by adding another DC current \( I_{dc} \) to the front section on top of the pulsed current applied. For comparison, we calculated the normalized total reflectivity of slot-QCLs with \( L_f = 80 \mu m \), and \( L_b = 96 \mu m \) under one-DC-current and two-DC-current pumping schemes as shown in Figs. 5(a) and 5(b), respectively. In Fig. 5(a), the group effective refractive index \( n_{\text{eff},f} \) is fixed at 3.415 (the central wavenumber is chosen as 970 cm\(^{-1}\)) while that of the back section \( n_{\text{eff},b} \) changes from 3.427 to 3.439, only one reflectivity maximum is observed indicating discontinuity of the tuning spectra. In Fig. 5(b), by changing \( n_{\text{eff},f} \) from 3.409 to 3.421 and scanning \( n_{\text{eff},b} \) from 3.427 to 3.439, maximum reflectivity can be obtained continuously within the entire scanning range, enabling much wider continuous tuning spectra. In addition, as seen from Fig. 2(b)), a larger continuous tuning range can also be achieved through active region design with flat gain profiles. Furthermore, by optimizing the slot configurations in both sections, i.e., slot number and slot spacing, it is possible to achieve relatively broad continuous tuning slot-QCLs at RT.

In conclusion, we have experimentally demonstrated tunable single-mode two-section slot-QCLs which have shown a relatively broad tuning range of 77 cm\(^{-1}\) (785 nm), corresponding to 7.8% relative tuning range, with a 31% continuous tuning range and an average SMSR of \( \approx 20 \) dB within the whole tuning range. The total tuning range is close to that of \( \approx 90 \) cm\(^{-1}\) with a SMSR of \( \approx 20 \) dB by using EC-QCLs with the same active region as our devices.\(^{34}\) The
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FIG. 5. (a) Calculated normalized total reflectivity of the slot-QCLs when varying $I_b$ only. The group effective refractive index of the front section $n_{\text{eff}, f}$ is fixed at 3.415, and that of the back section $n_{\text{eff}, b}$ is scanning from 3.427 to 3.439. (b) Normalized total reflectivity of the slot-QCLs when varying both $I_b$ and $I_a$. The group effective refractive index of the front section $n_{\text{eff}, f}$ is in the range of 3.409–3.421 and that of the back section $n_{\text{eff}, b}$ is from 3.427 to 3.439.

relatively broad single-mode tuning range combined with the easy device fabrication realized by only using conventional contact photolithography makes slot-QCLs appealing miniaturized mid-infrared sources for sensing and spectroscopy applications. Through numerical simulations, we showed that a much larger continuous tuning range can be achieved by separately pumping the front and the back sections through DC biases. Meanwhile, to achieve a broad tuning range at RT, the slot configurations can be optimized to reduce the spacing of the reflection peak while still maintaining high spectrum SSMRs. Due to the relatively high doping level, it is difficult to achieve CW operation in our current devices. However, it is possible to achieve CW operated slot-QCLs by using high performance QCL wafers, e.g., at $\sim 4.6 \mu$m. Further investigations are underway to realize RT broadly tunable single-mode CW slot-QCLs.

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