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Broadly continuously tunable slot waveguide quantum cascade lasers based on a continuum-to-continuum active region design

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We report our progress in the development of broadly tunable single-mode slot waveguide quantum cascade lasers based on a continuum-to-continuum active region design. The electroluminescence spectrum of the continuum-to-continuum active region design has a full width at half maximum of 440 cm^{-1} at center wavelength $\sim 10\text{ }\mu\text{m}$ at room temperature (300 K). Devices using the optimized slot waveguide structure and the continuum-to-continuum design can be tuned continuously with a lasing emission over 42 cm^{-1} , from 9.74 to $10.16\text{ }\mu\text{m}$, at room temperature by using only current tuning scheme, together with a side mode suppression ratio of above 15 dB within the whole tuning range. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4931444>]

Broadly tunable mid-infrared quantum cascade lasers (QCLs) have become indispensable laser radiation sources for spectroscopic applications due to their narrow laser linewidths and broad wavelength coverage, enabling simultaneous characterization of multiple trace gases with several tens of MHz resolutions.^{1,2} Significant improvements of laser performance in terms of tuning range and output power have been demonstrated by using external cavity (EC) QCLs^{3,4} or monolithic configurations, namely, linear arrays of distributed feedback (DFB) QCLs,^{5–7} sampled grating DFB QCLs (SGDFB-QCLs),^{8–10} and coupled-cavity QCLs.^{11–14} However, each geometry has its own intrinsic limitations. On one hand, the additional mechanical moving part in the EC-QCLs makes them vibration sensitive and relatively slow. The monolithic approach, on the other hand, usually requires complicated fabrication processes or suffers from high optical losses. Therefore, achieving tunable single-mode QCLs with easy fabrication and broad tunability remains a challenge. Recently, a new tuning scheme using slot waveguide structure has been proposed and experimentally demonstrated.¹⁵ The greatly simplified device fabrication processes together with relatively broad tuning range make the slot-QCL a promising candidate for spectroscopy and sensing applications. Nevertheless, the necessity of external heatsink temperature control of the prototype limits its practical applications. In this letter, we report the development of the mid-infrared single-mode slot-QCLs at $\sim 10\text{ }\mu\text{m}$, showing a continuous tuning range of $0.42\text{ }\mu\text{m}$, from 9.74 to $10.16\text{ }\mu\text{m}$, at room temperature (RT = 300 K) by using only the current tuning scheme.

The bandwidth of the gain profile is of critical importance to achieve a broad tuning range. In this work, we used a broad gain spectrum active region based on a continuum-to-continuum design in which the transitions take place

from the strongly coupled upper states to multiple lower states. The conduction-band diagram of our design with the calculated subbands envelope functions is shown in Fig. 1(a). The transitions with relevant oscillator strength are designed to occur from the upper states 4, 5, and 6 to the lower states 1, 2, and 3. Different from the previous design,¹⁶ in our design, two injector states are strongly coupled with the upper laser state with the energy splitting of $\sim 18\text{ meV}$ between states 4 and 6. A similar energy splitting has been demonstrated for achieving high power-efficient QCLs.¹⁷ The lower state is designed to be a quasiminiband similar to those in Refs. 18 and 19 so as to increase the number of radiative transition channels while still maintaining fast depopulation rate from the lower laser states. For the present work, the active region contains 35 periods of lattice matched $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ quantum wells and barriers based on the proposed continuum-to-continuum design. The whole waveguide structure was grown on a conducting InP substrate with a waveguide structure similar to that in Ref. 20.

The wafer was processed into $250\text{ }\mu\text{m}$ diameter circular mesas as well as $10\text{ }\mu\text{m}$ deep-etched Fabry-Perot (F-P) ridge lasers for preliminary performance characterization. The electroluminescence (EL) spectra of the mesas were measured using a Fourier transform infrared (FTIR) spectrometer in the step-scan mode with a cryogenically cooled mercury cadmium telluride (MCT) infrared detector and a lock-in amplifier under pulsed mode operation (80 kHz frequency and 1%–3% duty cycle). The F-P ridge lasers were tested at a frequency of 10 kHz with 200 ns pulsed width. Fig. 1(b) shows the light-current-voltage (LIV) characteristics of a typical $25\text{ }\mu\text{m}$ wide, 3 mm long F-P laser device, with the inset showing the measured EL spectrum at threshold current density and the device lasing spectrum at roll-over current density. The full width at half maximum (FWHM) is about 440 cm^{-1} at laser threshold current density, representing one

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FIG. 1. (a) Conduction band diagram of the continuum-to-continuum active region design under an applied electric field of 37 kV/cm with the modulus squared of the computed wave functions. The designed emission wavelength is around $10\text{ }\mu\text{m}$ at RT. The layer sequence of one period (in angstrom) starting from the injection barrier is **29/20/8/61/9/60/10/53/11/43/12/38/14/37/18/37/22/36/24/36/31/32/32/30**, where $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ barrier layers are in bold font and the underlined layers are doped (Si, $6 \times 10^{16}\text{ cm}^{-3}$). (b) Light output power vs current (L-I) and voltage vs current (V-I) curves in pulsed mode operation for a $25\text{ }\mu\text{m}$ wide and 3 mm long Fabry-Perot (F-P) ridge laser. The measured single-facet output power has been doubled for two laser facets. The inset shows the electroluminescence (EL) spectrum at threshold current density and the lasing spectrum at roll-over current density.

of the broadest gain spectra in the wavelength regime around $10\text{ }\mu\text{m}$. The broad gain profile does not strongly affect the laser performance in terms of output power and slope efficiency, which is attributed to the high injection ratio of the upper laser states²¹ and the fast depopulation rate of the lower laser states.¹⁹ For the F-P laser, taken into account both laser facets, the device shows a maximum peak power of $\sim 1.2\text{ W}$ and a slope efficiency of $\sim 1\text{ W/A}$. The broad gain spectrum together with the performance provided by the continuum-to-continuum active region design make it a good platform for the development of broadly tunable mid-infrared slot-QCLs.

The fabrication of the slot-QCLs is similar to that in Ref. 15, except for a double-channel device geometry, with laser ridges of $25\text{ }\mu\text{m}$ wide and $8\text{ }\mu\text{m}$ deep. The 3D schematic diagram and the detailed device structures are shown in Fig. 2. When designing the slot array structure, the following factors have been taken into considerations: first, the reflection peak spacing has to be reduced to enable continuous tuning. However, this will lead to a longer device for a certain slot number, due to the fact that the slot period is inversely proportional to the reflection peak spacing. Second, the $\Delta\omega_s$ (linewidth of the reflection peak) has to be small enough for implementing the Vernier-effect, as current-tuning shows small tuning coefficient. To achieve that, the slot periods for both sections should have close values. Third, the $\Delta\omega_p$ (reflection peak spacing difference) should be designed to be small than $\Delta\omega_s$ to ensure high side mode suppression ratio (SMSR). Therefore, multiple slots are required, as the linewidth of the reflection peak narrows with increasing the slot number. Given the above considerations, we chose the slot periods $L_f = 135.8\text{ }\mu\text{m}$ and $L_b = 142.9\text{ }\mu\text{m}$, leading to reflection peak spacings $\sim 11.4\text{ cm}^{-1}$ and $\sim 10.6\text{ cm}^{-1}$, respectively. The resulted $\Delta\omega_s = 0.8\text{ cm}^{-1}$ has been shown to be readily covered by using only current-tuning as verified by our previous experiment.¹⁵ The slot number $N = 25$ is chosen for both sections, leading to a $\Delta\omega_p = 0.75\text{ cm}^{-1}$, which is smaller than $\Delta\omega_s$. With the above parameters, the total length for current

FIG. 2. (a) 3D schematic diagram of the slot-QCLs. The front and back sections are electrically separated by a $150\text{ }\mu\text{m}$ gap in the top metal contact. (b) Optical microscopy image of the separation region where the lengths of the front section slot period, the gap in the contact, and the back section slot period are labelled by L_f , L_g , and L_b , respectively. The inset shows the magnified image of a single slot, with the slot width labelled by w . The corresponding parameters values are $L_f = 135.8\text{ }\mu\text{m}$, $L_g = 150\text{ }\mu\text{m}$, $L_b = 142.9\text{ }\mu\text{m}$, and $w = 3\text{ }\mu\text{m}$. (c) Scanning electron microscope (SEM) image of the output facet of the double-channel ridge device.

device is ~ 7.2 mm, which is quite long for conventional QCL devices. Though much smaller reflection peak spacing could be chosen, the device would require much longer cavity, which is beyond our processing capability.

As in the case of DFB QCLs, the laser facet effect has a significant impact on the slot-QCLs performance in terms of single-mode selection and output power. To utilize the facet effect,¹⁵ the distance between the laser facet and the adjacent slot was carefully cleaved to be equal to the corresponding slot period of each section, with a position cleaving accuracy of less than $3\ \mu\text{m}$. The as-cleaved laser bars were soldered epilayer-side up on copper submounts with indium solder for testing. The output power was collected using a calibrated thermopile detector. Spectral characterization was conducted using a FTIR at $0.2\ \text{cm}^{-1}$ resolution with a calibrated RT HgCdTe detector. As predicted in Ref. 15, applying two independent DC currents will greatly increase the continuous tuning range of slot-QCLs. To characterize the continuous tunability of the fabricated slot-QCLs, two operating conditions were applied. In the first condition (see Fig. 3(a)), the front section was driven above lasing threshold by a pulsed current $I_{f,p}$ with the back section unbiased. Two independent DC currents $I_{f,dc}$ (from 0 to 200 mA, with 20 mA step) and

$I_{b,dc}$ (from 0–1000 mA, with a 10 mA step) were supplied to each section to induce the local refractive index change caused by the Joule heating. In the other condition (see Fig. 3(b)), instead of the front section, the back section was driven above threshold by pulsed current $I_{b,p}$ while keeping front section unbiased. The current pulse duration was 150 ns with a pulse repetition rate of 10 kHz. In both cases, the pulsed and DC currents were combined through a bias-tee. The DC current sources and the FTIR were automatically controlled by our home-written Labview programme to fully characterize the devices. Different from the previous study,¹⁵ all the characterizations were performed at RT, thus no external heatsink temperature tuning was involved in the slot-QCL tuning characteristic testing. For both testing conditions, the laser output was collected from the front section.

The characteristics of a typical device are shown in Figs. 3(c) and 3(d). A total continuous tuning range of $42\ \text{cm}^{-1}$ (corresponding to 417 nm), which is 4.2% relative tuning range at center wavelength $\sim 10\ \mu\text{m}$, was demonstrated by the improved slot-QCLs at RT, with SMSR $> 15\ \text{dB}$ within the whole tuning range and 3 to 100 mW peak output powers. The moderate wavelength tunable range is mainly due to the limited wavelength selectivity of slot-QCLs. Similar to the case of EC-QCLs,¹⁹ the tunability of the slot-QCLs can be indicated by $\eta = \alpha_{sel}/\alpha_{sid}$, where α_{sel} and α_{sid} represent the total loss of the slot-selected mode and the total loss of the dominant side mode, respectively. A larger η leads to a narrower tunable range. As compared with the DFB-QCLs ($\eta \sim 0.8$),²² the slot-QCLs show closer values of α_{sel} ($\sim 21\ \text{cm}^{-1}$) and α_{sid} ($\sim 23\ \text{cm}^{-1}$) due to the relatively weak wavelength selectivity, thus leading to a larger value of $\eta \sim 0.91$ and a limited single-mode tunable range. According to Ref. 23, the SMSR is in linear relation with the $\Delta\alpha$ and Δg , where $\Delta\alpha$ and Δg are the total loss difference and the total gain difference between the slot-selected mode and the dominant side mode, respectively. During the measurements, we identified that the dominant side mode originated from the overlap of reflectivity spectra of the two sections around the gain maximum position. For the broad gain active region design, the Δg can be neglected due to the flat gain profile in a wider wavelength range. In this case, the $\Delta\alpha$ is a good indicator for the SMSR. As compared with the DFB-QCLs, the $\Delta\alpha$ of slot-QCLs shows smaller value than those in DFB-QCLs, thus leading to a lower SMSR with typical value $> 15\ \text{dB}$.

The lower peak power obtained from the slot-QCLs can be attributed to two main reasons: first, the laser shows multi-mode operation at high driving current when tuning for certain wavelength, thus limiting the range of the pulsed driving current available for single-mode operation. Therefore, during the experiment, we set the pulsed driving currents to be 1.1–1.4 times of the threshold values, leading to a much reduced output power. Second, the waveguide loss of the unpumped section severely deteriorate the performance of the pumped section, which can be identified by examining the threshold and the slope efficiency of the latter. For instance, when the front section is driving above threshold, device shows a threshold current density of $2.7\ \text{kA}/\text{cm}^2$ and slope efficiency of $150\ \text{mW}/\text{A}$, both of which are much lower than those from an F-P device with close size, indicating the

FIG. 3. (a) Schematic diagram of tuning configuration when the front section is biased above threshold. (b) Schematic diagram of tuning configuration when the back section is biased above threshold. (c) The peak output power as a function of the wavenumber. (d) Tunable single-mode spectra of slot-QCLs at heatsink temperature of 300 K.

strong absorption from the unpumped section. It is also noted that the device shows strong power variation, which mainly originates from the variation of the pulsed driving currents in the experiments.

Detailed examinations reveal that the wide continuous tuning range was realized by two mechanisms: the current-induced continuous tuning of a single-mode and the Vernier-effect between the front and back sections. The first effect is shown in Figs. 4(a) and 4(b), where $I_{f,dc}$ and $I_{b,dc}$ were varied, respectively, with a fixed DC current in the other section. According to Figs. 4(a) and 4(b), current tuning coefficients of $dn_{eff}/dI_{f,dc}$ and $dn_{eff}/dI_{b,dc}$ can be calculated. A value of $\sim 1.4 \times 10^{-5} \text{ mA}^{-1}$ was obtained for both sections due to the close size of each section. The obtained value is much smaller than that ($\sim 5 \times 10^{-5} \text{ mA}^{-1}$) in Ref. 15, which can be attributed to the much larger device size. However, the wide tuning behavior is realized mainly through the second effect, namely, the Vernier-effect.

To illustrate the Vernier-effect, two single-mode spectra at $\sim 1014 \text{ cm}^{-1}$ and $\sim 1025 \text{ cm}^{-1}$ were chosen (Fig. 4(c)). The first spectrum was testing at $I_{f,dc} = 0.00 \text{ mA}$ and $I_{b,dc} = 320 \text{ mA}$, and the latter one was recorded at $I_{f,dc} = 0.00 \text{ mA}$ and $I_{b,dc} = 120 \text{ mA}$. The detailed modeling was similar to that formulated in Ref. 15. In this work, we have assumed that the distance between the laser facet and the adjacent slot is equal to the slot period. The single slot field reflection coefficient (r_s) and transmission coefficient (t_s) were determined to be ~ 0.015 and ~ 0.99 , respectively, using finite-difference time-domain (FDTD) package Lumerical software. Meanwhile, using the $1/L$ approach, a linear least-squares fit to the measured value give a loss $\alpha = 10.1 \text{ cm}^{-1}$. By using the same procedure as describe in Ref. 15, the calculated Vernier-effect-induced wavelength red shift is shown in Fig. 4(c), where the power reflectivity is defined as the ratio between the input optical power and the reflected power by the slot array. Our results clear show that refractive index change as

FIG. 4. (a) Continuous tuning lasing spectra at $I_{b,dc} = 0.20 \text{ A}$, and $I_{f,dc} = 0.16 \text{ A}$, 0.18 A , and 0.20 A , respectively. (b) Continuous tuning lasing spectra at $I_{f,dc} = 0.20 \text{ A}$, and $I_{b,dc} = 0.02 \text{ A}$, 0.04 A , and 0.06 A , respectively. (c) Upper figure shows the selected single-mode spectra at $\sim 1014 \text{ cm}^{-1}$ (red) and $\sim 1025 \text{ cm}^{-1}$ (black). Middle and lower figures show the redshift of the emission wavelength when varying the $I_{b,dc}$ from 120 to 320 mA. The red dashed line is the power reflectivity from the back section, and the blue solid line is the power reflectivity from the front section.

FIG. 5. Far-field profile (black) of the slot-QCL emitting at wavelength of $\sim 1000 \text{ cm}^{-1}$. The red curve shows the numerical simulation result using experimentally obtained parameter values. The inset shows the single-mode emission at wavelength of $\sim 1000 \text{ cm}^{-1}$.

small as ~ 0.003 can lead to a significant change of the overlapping wavelength, from ~ 1025 to $\sim 1014 \text{ cm}^{-1}$, which is in agreement with the experimental data.

The beam quality of the slot-QCLs was further investigated by measuring the far-field profile of the output along the slow axis (x direction in Fig. 1). The far-field profile at center wavenumber of $\sim 1000 \text{ cm}^{-1}$ is shown in Fig. 5, where the numerical simulation using the experimental parameters is also shown for comparison. Excellent agreement is achieved between the experimental and numerical results. The far-field profile exhibits a fundamental mode (TM_{00}) with a FWHM of $\sim 26^\circ$.

In conclusion, we have demonstrated RT broadly tunable single-mode slot-QCLs at wavelength $\sim 10 \mu\text{m}$, with a continuous tuning range of 42 cm^{-1} (417 nm), corresponding to 4.2% relative tuning, a SMSR of above 15 dB within the whole tuning range, and a single-lobed symmetric far-field pattern. The tuning range demonstrated is comparable with those obtained using the SGDFB-QCLs.^{8,9} Though the current device shows a lower output power than that reported in SGDFB-QCLs,⁸ the slot-QCL shows clear advantages in terms of easy device fabrication, i.e., optical lithography patterning and no InP re-growth process. The latest demonstration shows a significant step towards practical applications of slots-QCLs and makes them promising

tunable single-mode laser radiation sources given their fabrication simplicity.

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