Stable single-mode 20-channel uniform buried grating DFB QCL array emitting at ~ 8.3 μm

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Received: 16 November 2021 / Accepted: 24 February 2022 / Published online: 21 March 2022
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Abstract
A 20-channel distributed feedback (DFB) quantum cascade laser (QCL) arrays based on uniform buried grating have been demonstrated. In pulsed mode, peak power reaches 80 mW and slope efficiency reaches 167 mW/A for 2.5 mm-long laser in the arrays at room temperature. The loss difference of two band-edge mode increases when reflectivity of the front facet becomes small, which prevents the mode hopping. The device shows linear tuning after the anti-reflectivity coating is deposited in the front facet, maintaining peak power of 64 mW. The whole chip covers a tuning range of 64 cm⁻¹, centering at 8.3 μm, with side-mode-suppression-ratio over 20 dB at room temperature.

Keywords QCL array · Uniform buried grating · Band-edge mode · Anti-reflectivity coating

1 Introduction
Mid-infrared quantum cascade lasers (QCLs) are unipolar semiconductor lasers based on resonant tunneling and optical transitions within the conduction band of a multi-quantum well structure (Faist et al. 1994). There are various application including gas sensing (Kosterev et al. 2002), industrial process monitoring (Yao et al. 2012), spectroscopy (Namjou et al. 1998), and free space communication (Corrigan et al. 2009), which demands widely tunable and single-mode QCLs. External cavity (EC)-QCLs are broadly tunable light sources and have achieved a tunability of over 300 cm⁻¹ (Centeno et al. 2014). However, the system is usually bulky and requires fine optical alignment. DFB-QCLs are compact with side-mode-suppression-ratio (SMSR) about 30 dB. In terms of practical application, molecular trace gas detection based on a DFB QCL reaching a sensitivity of nine parts per billion is proposed (Gadedjisso-Tossou et al. 2020). Although a single DFB-QCL has a limited tuning range of a few cm⁻¹ (~ 10 cm⁻¹) via temperature tuning, we can still achieve...
wide tunability by fabricating a large amount lasers of different periods of gratings in one chip (Lee et al. 2009; Rauter et al. 2015). In this way, we can develop this tunable source called DFB-QCL arrays combining the advantages of external cavity and DFB devices, and the array has reached an impressive tunability above 230 cm\(^{-1}\) (Slivken et al. 2013).

However, DFB-QCL arrays still have the problem of mode hopping which can be detrimental for this single-mode device. In most case, buried grating DFB-QCL will have problem of random cleaved facets. Due to the similar amount of loss of the two band-edge, competition between high-frequency mode and low-frequency mode will always happen, especially under high working temperature or large injection current. In order to guarantee stable single-mode operation, three methods are mainly used to solve the problem. A quarter-wave phase shift (\(\lambda/4\) PS) (Shi et al. 2014; Zhang et al. 2014) was introduced, which can relieve the competition between the two band-edge modes, to make lasers work in defect mode. However, the fabrication of \(\lambda/4\) PS can be quite complex and is also difficult to achieve accuracy. Gain-coupled DFB laser (Luo et al. 1990) is a good way for conventional semiconductor laser to work in stable single-mode operation, but it has problem when applied in QCL since the large loss as a result of the etched active region. Loss coupling is effective method in this case, which helps increase the loss difference between high-frequency mode and low-frequency mode. With proper reflectivity facet coating, DFB-QCL lasers can achieve stable single-mode even under high temperature or large current working condition (Lu et al. 2011). By optimizing the thickness of coatings at front and rear facet (Maulini et al. 2009; Bai et al. 2011), we can improve the single-mode reliability of DFB-QCL as well as maintain its output power and wall-plug efficiency (WPE). In addition, emission wavelength and grating duty are significant factors for controlling the loss of two band edge mode according to our research, which can guide to fabricate steady single-mode DFB-QCL arrays.

In this paper, we designed and fabricated an array of 20 buried grating DFB-QCLs monolithically integrated on a single chip. The grating period was varied from 1.268 to 1.344 \(\mu\)m, maintaining single-mode emission at different wavelengths (from 8.08 to 8.53 \(\mu\)m) with an SMSR above 20 dB was obtained in pulsed mode at a duty cycle of 1% (20 kHz,0.5 \(\mu\)s) up to a temperature of 70 \(^\circ\)C without mode hopping. The entire chip covers a range from 1173 to 1237 cm\(^{-1}\) (a whole coverage of 64 cm\(^{-1}\)), with the frequency spacing between adjacent lasers is about 3.4 cm\(^{-1}\). The spacing between adjacent lasers is adequately small that ever single laser can cover the spacing through its temperature tuning. We discover that there are close relationship between emission wavelength, grating duty cycle and the loss of two band-edge mode besides the random phase of cavity facet. Finally, we solve the mode hopping which may be caused by these factors by applying anti-reflectivity (AR) coating.

2 Simulations

We first calculated the loss of high frequency and low frequency based on transfer matrix simulation. (Patchell et al. 2005; Wang et al. 2018). Figure 1a indicates that the loss of high frequency mode hardly changes as the reflectivity decreases while the loss of low frequency mode increase sharply. We can predict that the low-frequency mode will not lase when the reflectivity of the front facet is low, however, the losses of the two band-edge mode are almost the same when the front facet is not deposited the AR coating (corresponding
to a reflectivity of 0.27). When lasing wavelength is around 8.20 μm, the high-frequency mode loss is 0.2914 cm⁻¹, and low-frequency mode loss is 0.2850 cm⁻¹. In that case, the emission of the two band edge mode can be uncertain, which might be determined by the specific wave-length and duty cycle of the gratings. The duty cycle of the gratings is equal to the ratio of the width of the grating of high refractive index to the period.

For practical reasons, we calculated the loss of the high-frequency mode and low-frequency mode when different periods of gratings applied in DFB lasers. The refractive index at the top and bottom of the grating was set to be 3.1836 and 3.1778 calculated by MATLAB, respectively, assuming a grating etching depth of 130 nm, keeping duty cycle of grating to be 50%. In order to remove the influence of the random phase of cleaved facet, we first set the cavity length of each laser to 2000 × in period, corresponding to be 2552–2632 nm, which means every laser have no phase difference with others. Then we scanned the loss corresponding to the wavelength from 8.0 to 8.6 μm with a step of 0.001 μm in each period. Figure 1b demonstrates that although the losses of the high-frequency mode and low-frequency are quite similar, they still exist discrepancy especially when the wavelength deviates the bal-anced wavelength (the wavelength at which two band edge mode are exactly the same), approximately 8.24 μm for this device. That is to say, when the designed lasing wavelength is 8.24 μm (corresponding to the period of 1.296 μm), the balanced reflectivity (the corresponding reflectivity of front facet when two band edge mode are same) is exactly 0.27. The loss difference between two band edge modes increase distinctly when the wavelength is > 8.24 μm (especially when it is > 8.36 μm), which will signifi-cantly improve the possibility of high-frequency mode emission. On the con-trary, lasers are more likely to lase at low-frequency mode when wavelength is < 8.24 μm. It is because long-wavelength high-frequency will suffer severely from mirror loss. When the designed lasing wavelength is > 8.24 μm, the balanced reflectivity will slightly lower than 0.27, which means the high-frequency loss will take the lead when no AR coating is applied, and vice versa. We can predict mode hopping will occur around 8.24 μm by the result. The influence of wavelength would further amplify if phase difference is introduced.

Also, we obtain the relationship between duty cycle of the gratings and the loss differ-ence of two band edge modes, and we set the duty cycle in different size, from 10 to 90%, and the period to 1.296 μm to remove the influence of wavelength. As shown in Fig. 1c, when duty cycle is 50%, the difference of two band edge modes is only 5.0×10⁻⁴ cm⁻¹, which can be neglected. However, when duty cycle be-comes larger, the loss of low-fre-quency mode increase more evidently than high-frequency mode, and the loss difference of

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**Fig. 1** a The mode loss of high- (circle) and low-frequency (triangle) mode, and the differential mode loss (square) between the two band-edge modes versus reflectivity. The inset shows calculated mode loss spec-trum without AR. b The mode loss of high- and low-frequency mode, and the differential mode loss versus wave-length. c The mode loss of high- (circle) and low-frequency (triangle) mode, and the differential mode loss (square) versus duty cycle of gratings
two band edge modes increase 1.721 cm$^{-1}$ when duty cycle is 90%, which would contribute to high-frequency mode emission; When duty cycle becomes smaller, the loss of high-frequency mode grows faster, with the loss difference rising to 1.261 cm$^{-1}$ when duty cycle is 10%, which lead the low-frequency to lase. It is because when the duty cycle become larger, the cleaved point is more likely to be in the low-index part of the grating, in which the high-frequency mode has more of the electric field concentrated. Therefore, high-frequency modes more likely to lase when duty cycle is > 50%, and vice versa. In the practical fabrication of DFB-QCL arrays, the grating period deviation will lead to the mode hopping due to the change of two mode loss. Not exactly the same duty cycle in the practical etching processing, especially wet etching, will also cause this problem.

3 Experiments and results

Figure 2a shows the front facet of QCL array, and it is mounted epi-side down on an AlN for further heat dissipation and wires bonded is revealed in Fig. 2b. The QCL core structure was grown on a n-doped (Si, 3 × 10$^{17}$ cm$^{-3}$) InP substrate by molecular beam epitaxy (MBE), and the InP layers were grown by metal–organic chemical vapor deposition (MOCVD). The epitaxial layer sequence, starting from the n-doped InP substrate, was as follows: 3.5 μm doped lower InP cladding layer (Si, 5 × 10$^{16}$ cm$^{-3}$), 0.5 μm lower InGaAs waveguide layer (Si, 2 × 10$^{16}$ cm$^{-3}$), In0.53Ga0.47As/In0.52Al0.48As QCL active core, 0.5 μm upper InGaAs wave-guide layer (Si, 2 × 10$^{16}$ cm$^{-3}$), 3.5 μm doped upper InP cladding layer (Si, 5 × 10$^{16}$ cm$^{-3}$), 0.2 μm gradually doped InP layer (Si, from 1 × 10$^{17}$ cm$^{-3}$ to 5 × 10$^{17}$ cm$^{-3}$), and 0.6 μm highly doped InP contact layer (Si, 6 × 10$^{18}$ cm$^{-3}$). The active core based on single-phonon continuum depopulation comprises 35 periods. The layer sequence in one period (in angstrom) from the injection barrier: 3.9/1.3/0.95/5.1/0.85/5.0/0.95/4.6/1.6/3.5/2.2/2.9/1.8/2.7/1.9/2.6/2.0/2.4/2.5/2.45/3.1/2.3 (Wang et al. 2017) where the bold represents barriers and the underlined are layers with Si doped to 1.1 × 10$^{11}$ cm$^{-2}$. Then the top cladding was removed down to the upper InGaAs layer, which was then etched to a depth of about 130 nm to form gratings of different periods. The grating periods were ranged from 1.268 to 1.344 μm (duty cycle σ = 50%) with the entire chip covering the wavelength band from 8.08 to 8.53 μm, and the grating of 1.27 μm is shown in Fig. 2c, which well satisfies the Bragg condition assuming an effective refractive index (neff) of 3.18 calculated by our simulation according to our material system.

After the upper InP waveguide layer regrowth, 17-μm-wide laser ridges, spaced 80 μm apart from the adjacent, were defined on it by etching the surrounding area. The

Fig. 2  a Microscope image of the array front facet. b The array of 20 lasers is mounted epi-side down on an AlN heat sink. c SEM of the buried gratings of 1.27 μm in the InAlAs layer
intermediate area between the ridges is buried in semi-insulating InP (Fe) by MOVPE to guarantee heat dissipation. A 450-nm-thick SiO2 layer was deposited by plasma enhanced chemical vapor deposition (PECVD) for insulation around the ridges. Then, 3 μm-width electrical injection windows were opened on the ridges, and the top electrical contact was provided by a Ti/Au layer deposited by electron beam evaporation. An additional 5 μm-thick gold layer was subsequently electroplated to further improve heat dissipation. After the wafer was thinned down to 120 μm and back contacts were formed with Ge/Au/Ni/Au, the laser bars were cleaved to a length of 2.5 mm. High-reflectivity (HR) coating consisting of Al2O3/Ti/Au/Ti/Al2O3 (200/10/100/10/120 nm) and AR coating of Al2O3/Ge (792/62 nm) were deposited at the rear facet and the front facet, respectively. The calculated reflectivity of front facet is below 10−5 at the wavelength of 8.3 μm. The total chip was mounted epi-side down on AlN heat sinks with indium solder and finally wires bonded to an external circuit board.

We first present the result of 2.5 mm-long laser array which does not apply AR coating. The spectra for 20 lasers of this array are shown in the Fig. 3a. All the lasers work in steady single-mode condition with an SMSR above 20 dB. However, the lasing frequencies of 20 lasers are not change completely uniformly. To be more specific, 14 of all lasers are lasing on the high-frequency mode, and the rest of 6 are lasing on the low-frequency mode. The emission frequencies of lasers #8–#20 are spaced regularly apart, but it appears mode hopping of 4.5 cm⁻¹ when it comes to laser #7 (8.25 μm), which is well consistent with our previous simulation results. The lasers operate on the high-frequency mode at long wavelength, and the lasers mainly work on the low-frequency mode at short wavelength.

Figure 3b shows the pulse power-current–voltage (P-I-V) curve of the 4 DFB lasers in room temperature (RT). The peak power reaches 80 mW for one 2.5 mm-long laser, corresponding to 4 μW per pulse, and threshold currents (Ith) for all DFB lasers ranged from 1.16 to 1.26 A, corresponding to threshold current densities (Jth) of 2.73–2.96 kA/cm² at 20 °C. The threshold voltage (Vth) is 10.18 V and the slope efficiency reaches 167 mW/A. All measurements were taken under pulsed operation at a duty cycle of 1% (20 kHz, 0.5 μs) at RT. The spectra and emission power were measured with a calibrated thermo-pile detector and a Fourier transform infrared (FTIR) spectrometer, respectively.

Then the front facet of our 2.5 mm-long array was deposited AR coating of Al2O3/Ge (792/62 nm) in order to improve the single-mode selection. We evaporated

![Fig. 3](image-url) a The spectra of 20 lasers in the array without AR coating. b P-I-V of the laser #8, 10, 12, 14 in the array without AR coating
two layer of Al2O3 and Ge, whose refractive index are 1.55 and 4.007 at wavelength of 8.3 μm respectively. We deposited 792 nm of Al2O3 and 62 nm of Ge on the front, the calculated reflectivity of which is below 0.01. New spectra were measured after we applied the optimized AR coating of Al2O3/Ge. Figure 4a shows that all of 20 lasers are operating on the high-frequency mode, and exhibit a larger SMSR than before. Every of 20 lasers is spaced regularly apart (3.3 cm⁻¹), and the entire chip covers wavenumber from 1173 to 1237 cm⁻¹ (total 64 cm⁻¹).

Figure 4b shows the pulse power-current–voltage (P-I-V) curve after AR was coated of the same 4 DFB lasers in RT. It sees an evident drop in all 4 lasers’ peak power, and the output of laser #14 decreases to 64 mW. It is easy to understand since the extremely low reflectivity causes a larger mirror loss in the front facet which would lead to drop in output power. Threshold currents (Ith) for the all DFB lasers rise to 1.25–1.47 A, corresponding to threshold current densities (Jth) of 2.94–3.46 kA/cm² at 20 °C. The threshold voltage (Vth) also rises to 10.46 V while the slope efficiency decline slightly to 125 mW/A.

The result proves that it is a trade-off when applying AR coating of suitable thickness to make a balance between the output power and single-mode selection. In addition, the emission wavelength of laser #10 was measured by Bristol 771 Laser Spectrum Analyzer in pulse mode during a period of 2000s as shown in Fig. 5. It is clearly demonstrated that the lasers in the QCL array have good frequency stability, and the slight wavelength

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**Fig. 4** a The spectra of 20 lasers in the array after AR coating is applied in the front facet. b P-I-V of the laser #8, 10, 12, 14 after AR is applied

**Fig. 5** The emission wavelength of laser #10 during period of 2000s after AR is applied
fluctuation was due to the ambient temperature change and heat caused by chirp effect. It is promising to work outside for gas sensing for long time with TEC and mode locker.

The emission spectra of laser #10 is shown in Fig. 6. The measurements were performed using a NI-COLET 8700 FTIR spectrometer with 0.25 cm$^{-1}$ resolution in a rapid scan mode (Yan et al. 2015), and the heat sink temperatures were varied from 0 to 70 °C with the increment of 10 °C. The center wave-number is 1206.979 cm$^{-1}$ at 0 °C and shifts to 1201.676 cm$^{-1}$ at 70 °C with a temperature tuning coefficient $\Delta \nu/\Delta T = -0.0758$ cm$^{-1}$ K$^{-1}$, as is illustrated in the inset of Fig. 6. The device performs perfect linear tuning, which means no mode hopping occur when heat sink temperatures are 0–70 °C. Moreover, we conducted far-field test by Pyrocam IV beam profiling camera after focusing by a lens at the duty cycle of 1%, and the beam widths of X, Y axis are 1.18 and 1.10, respectively, and the inset indicates the single-lobe lateral pattern measured at a distance of 500 mm from the lens.

4 Conclusion

In conclusion, we have demonstrated a 20-channel DFB-QCL array based on uniform buried grating. We obtain the relationship between emission wavelength, duty cycle and loss of the two band edge modes, and predict the mode hopping in device without
AR coating. The device covers a range from 1173 to 1237 cm\(^{-1}\) (a whole coverage of 64 cm\(^{-1}\)) operating in steady single-mode without mode hopping after AR coating. The maximum peak output power reaches 80 mW and the slope efficiency reaches 167 mW/A with SMSR over 20 dB without AR coating, and maintain 64 mW after AR coating is applied. For further improvement, the spacing between two adjacent lasers can be optimized to get higher output power and working temperature.

**Acknowledgements** This work was supported by the National Key Research and Development Program of China (2018YFA0209100), the National Natural Science Foundation of China (Grant Nos.61991430, 61774146, 61790583, 61674144, 61774150 and 61805168), the Beijing Municipal Science & Technology Commission (Grant No. Z20110000 4020006) and the Key Projects of CAS (Grant Nos. 2018147, YJKYYQ20190002, QYZDJ-SSW-JSC027 and XDB43000000).

**Declarations**

**Conflict of interest** The authors have not disclosed any conflict of interests.

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