10-W pulsed operation of substrate emitting photonic-crystal quantum cascade laser with very small divergence

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Abstract

High-power broad area substrate emitting photonic-crystal distributed feedback (DFB) quantum cascade lasers (QCLs) emitting around 4.73 μm is reported. Two-dimensional centered rectangular photonic-crystal (CRPC) grating is introduced to enhance optical coherence in large area device. Main lobe far-field radiation pattern with a very small divergence angle of about 0.65° × 0.31° is obtained. A record peak output power for vertical emitting QCLs exceeding 10 W is obtained with high reflectivity (HR) coating. Robust single longitudinal mode emission with a side mode suppression ratio (SMSR) of 30 dB is continuously tunable by the heat sink temperature up to 65°C.

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Background

Recent successive performance breakthroughs of vertical emitting quantum cascade lasers (QCLs) [1-4] have aroused more attention and further research into this field. Due to easy packaging [5], lacking of catastrophic optical damage [6] and high beam quality, vertical emitting QCLs become a prominent candidate as ideal source in mid-infrared spectrum range.

The previous reported vertical emitting QCLs [7-9] were limited to pulsed mode operation with output power below 1 W. Subsequently, with the advent of epilayer-down bonding technology for substrate emitting quantum cascade lasers (a kind of vertical emitting laser with light out from the substrate side, SE-QCLs) [10], continuous wave (CW) operations were demonstrated with second-order distributed feedback (DFB) grating stripe [11,12] and ring [13] cavity laser. However, for some applications, such as remote detection and laser-induced blinding, high pulsed power is more desirable than CW operation. Experiments [14] have verified the positive correlation between power and emitting width for edge emitting QCLs. Similarly, 60- and 100-μm-wide second-order DFB SE-QCLs emitting peak power of 1.8 and 2.4 W at room temperature were achieved respectively [15], while simply increasing the width of devices leads to degraded spatial beam properties [14]. Two-dimensional (2D) photonic-crystal (PC) DFB grating is a periodic structure with great potential, which is not only compatible to a large gain medium size but also providing effective modulation of longitudinal mode (spectrum) and transverse mode (far-field in transverse direction) simultaneously [16-18]. Photonic crystal vertical emitting QCLs were designed to produce vertical radiation from rectangle aperture (200 μm × 200 μm) with narrow divergence angle of 2.4° × 1.8° [2].

In this paper, we present a promising approach based on 2D centered rectangular photonic-crystal (CRPC) theory to fabricate broad area substrate emitting mid-infrared quantum cascade laser. A compromised cross angle θ for CRPC lattice is chosen to enhance the coupling strength in the transverse direction without degradation of single longitudinal mode performance after numerical simulation. At room temperature, the laser
emits total optical power as high as 10 W with a very small divergence far-field angle below 1° in two directions.

Methods
Structure and simulation
Figure 1a shows three-dimension (3D) sketch of the substrate emitting device. The active region of QCL structure is based on strain compensated In$_{0.67}$Ga$_{0.33}$As/In$_{0.36}$A$_{0.64}$As quantum wells and barriers, identical with ref. [19]. A 1.54-μm active region is sandwiched between two 300-nm-thick InGaAs layers grown by solid source molecular beam epitaxy (MBE). The CRPC structure with cross angle $\theta$ of 80° (Figure 1b) is defined on the upper InGaAs layer using double-exposure holographic lithography (DEHL) technique [20]. Then, 3.0 μm InP cladding layer and 0.8 μm high-doped InP contact layer are grown by metal organic chemical vapor deposition (MOCVD). In our design, embedded CRPC lattice structure between the high-index InGaAs layer and low-index InP cladding, as shown in Figure 1c, is adopted in order to get the waveguide loss smaller than surface metallic lattice structure because the latter will introduce heavily metallic ohmic losses at the interface between metal and semiconductor.

2D photonic-crystal geometry obtains vertical coherent oscillation radiation over a broad area based on the band edge effect [21] with an increased optical path length, which leads to a gain enhancement. Typical square and hexagonal lattice have been principally investigated for years. As a novel structure, centered rectangular lattice structure [22,23] has been primarily investigated for years since it may have potential for a combination of advantages from square and hexagonal lattice. In order to make a comparison among the three types of PC structure and obtain optimized design parameters in our vertical emitting QCLs, we analyze the band structure and coupling coefficient of different types of 2D photonic-crystal.

By using bandsolve module of Rsoft, based on 2D plane wave (PW) expansion method [24], we first analyze the band structure for different types of lattice and calculate the number of band edge longitudinal modes simultaneously. Figure 2 shows the enlarged band structure near the $\Gamma$ point of lattice PC with cross angle $\theta$ ranging from 90° to 60° in a step of 10°, and the insets at the bottom of each picture depict the pattern of different types of photonic-crystal. The number of band edge resonant fundamental longitudinal mode depends on the lattice structure. There are both four modes for square (Figure 2a) and centered rectangular lattice (Figure 2b,c) while six modes presented for hexagonal lattice (Figure 2d). It indicates that square and centered rectangular lattices are more likely to realize stable single longitudinal mode oscillation.

We next investigate the impact of cross angle $\theta$ on the in-plane coupling coefficient. Given the chosen exposure period $a_0$ and fixed radius of cylinder $r$, the coupling coefficients only change with the lattice cross angle $\theta$. In the inset of Figure 3, the primitive translation vectors labeled $\vec{a}_1 = a(0, 1)$, $\vec{a}_2 = a(-\sin \theta, \cos \theta)$ and the primitive reciprocal lattice vectors labeled $\vec{b}_1 = l\beta(\cos \theta, \sin \theta)$, $\vec{b}_2 = m\beta(-1, 0)$ where, $a = \frac{a_0}{\sin \theta}$, $\beta = \frac{2\pi}{a_0}$.

We calculate the coupling coefficients by using the following expression [25]:

$$\begin{align}
\kappa_1 &= \frac{2\pi \Delta n}{\lambda} \int \frac{dz}{A} \int dx \exp \left[-i \left(\vec{b}_1 - \vec{b}_2\right) \cdot r\right] \quad (1) \\
\kappa_2 &= \frac{2\pi \Delta n}{\lambda} \int \frac{dz}{A} \int dx \exp \left[-i \left(\vec{b}_1 - \vec{b}_2\right) \cdot r\right] \quad (2) \\
\kappa_3 &= \frac{2\pi \Delta n}{\lambda} \int \frac{dz}{A} \int dx \exp \left[-i \left(\vec{b}_1 - \vec{b}_2\right) \cdot r\right] \quad (3)
\end{align}$$

For $(l = m = 2)$ coupling order:

![Figure 1](image.png)

**Figure 1** 3D sketch, SEM, and cross section of the lattice. (a) Three-dimension (3D) sketch of a device. (b) Scanning electron microscope (SEM) image for centered rectangular photonic-crystal grating. (c) Cross section of the lattice after MOCVD regrowth.
\[ \vec{b}_1 - \vec{b}_{-1} = \vec{b}_2 - \vec{b}_{-2} = 2 \sqrt{l^2 + m^2 \beta} = 4 \beta, \quad \vec{b}_1 - \vec{b}_{-2} = l \beta \sin \theta, \quad \vec{b}_1 - \vec{b}_{-1} = m \beta \cos \theta \]

where \( A \) is the area of the primitive cell of the reciprocal lattice, refractive index contrast \( \Delta n = 0.008 \) derived from 1D effective index method [26], \( a_0 = 1.49 \mu m \), and \( r = 0.5 \mu m \).

The coefficient \( \kappa_1 \) accounts for distributed reflection-like diffraction into the counter propagating in-plane wave, such as from \( \vec{b}_1 \) into \( \vec{b}_{-1} \) or from \( \vec{b}_2 \) into \( \vec{b}_{-2} \). The coefficient \( \kappa_2 \) and \( \kappa_3 \) represent diffraction into the oblique in-plane wave vectors \( \vec{b}_1 \) into \( \vec{b}_2 \) and \( \vec{b}_1 \) into \( \vec{b}_{-1} \). Figure 3 shows the calculated coupling coefficient \( \kappa_1, \kappa_2, \) and \( \kappa_3 \) as a function of lattice cross angle \( \theta \). We find that when \( \theta \) changes from 90° to 60°, \( \kappa_1 \) slightly reduces from 2.47 to 2.14 cm\(^{-1}\). Being different from \( \kappa_1 \), the values of \( \kappa_2 \) and \( \kappa_3 \) are identical 7.96 cm\(^{-1}\) at the beginning; then, \( \kappa_2 \) rapidly increases to 17.86 cm\(^{-1}\) and \( \kappa_3 \) reduces to 0.35 cm\(^{-1}\). In order to obtain uniform modal intensity distribution throughout the device, the coupling strength \( \kappa L \), where \( L \) is the device length in the coupling direction, must be or close to 1 [27]. This means the centered rectangular lattice, especially for \( \theta = 80^\circ \), enjoys an enlarged \( \kappa_2 L_1 \) (\( L_1 = 0.039 \text{ cm} \)) = 0.45 and reduced \( \kappa_3 L_2 \) (\( L_2 = 0.4 \text{ cm} \)) = 1.9 compared to square lattice that 0.3 and 3.2, respectively. Therefore, combining with the preceding analysis of the band structure, vertical emitting laser adopting centered rectangular lattice is a good compromise between square lattice and hexagonal lattice to achieve both single longitudinal mode operation and high efficiency vertical emitting.

**Device fabrication**

To make the buried CRPC grating, the top InP cladding was removed down to the upper InGaAs layer. A second-order CRPC lattice was defined on the upper InGaAs layer using DEHL technique and subsequently etched to a depth of 150 nm by wet chemical etching. The first exposure with a grating period of 1.49 \( \mu \text{m} \) was set along longitudinal direction, and the second exposure with the same period was oblique with a cross angle \( \theta \) of 80°. The fabrication of our devices presented in this paper started from a CRPC lattice MOCVD regrowth.
Results and discussions

Device testing was done on an automatic temperature control stage. For electro-optical characterization, the substrate emitting output power was measured with a calibrated thermopile detector that collected laser radiation. The lasing spectra measurement was performed using a Fourier transform infrared spectrometer with a resolution of 0.125 cm\(^{-1}\) in rapid scan mode. 2D far-field was done by placing a mercury cadmium telluride (MCT) detector on a 2D stepped motor control translation stage (minimum step of 100 \(\mu\)m, maximum scans range of \(4.5 \times 4.5\) cm\(^2\)), placed at 25 cm away from the laser. After collecting lock-in amplification of the detector signal from the far-field, we processed the data causing the wave vector of \(a\) to connect a line of shoulder peak and main peak between \(x\) and \(y\) axis in Figure 1a. At low injection current of 33.0 A (Figure 5a), a small divergence far-field was obtained and the full width at half maximum (FWHM) of the main lobe emission cone is \(\theta_x \times \theta_y = 0.65^\circ \times 0.31^\circ\). At higher current levels (Figure 5b), an increased broadening of the main lobe (\(1.1^\circ \times 0.45^\circ\)) is observed due to more pronounced thermal effects especially for broad area laser related to self-focusing effect [28]. Figure 5c shows the 1D far-field in \(\theta_x\) direction derived from Figure 5a. The small dotted lines labeled TM\(_{00}\), TM\(_{03}\), and TM\(_{06}\) correspond to 1D fitting of the different order transverse far-field distribution. TM\(_{03}\) and TM\(_{06}\) is the third- and sixth-order transverse mode, respectively. In this direction, the far-fields exhibits hybrid transverse mode. Based on the measured 2D far-field intensity distributions (Figure 5a,b), we calculate the proportion of each transverse mode. At 33.0 A, TM\(_{00}\) weights with 35.7\%, TM\(_{03}\) 34.7\%, and TM\(_{06}\) 29.6\%. At 53.3 A, TM\(_{00}\) increased to 39.1\%, TM\(_{03}\) down to 32.7\%, and TM\(_{06}\) 28.2\%. In addition, we find that the whole electric field intensity distribution in \(\theta_x\) direction is slightly tilted by connecting a line of shoulder peak and main peak because the wave vector of \(a\) is oblique with \(a\) by an angle of \(80^\circ\). The emergence of TM\(_{03}\) and TM\(_{06}\) indicates that their losses are insufficient to suppress the gain. Figure 5d shows the 1D far-field in \(\theta_y\) direction.

Providing that the fundamental transverse mode (TM\(_{00}\)) has priority to lase, vertical emitting devices with PC grating are capable of providing large scale of emitting apertures. So substrate emitting CRPC quantum cascade lasers will emit more light energy propagating along highly compressed spatial paths. Figure 5 shows the measured far-field intensity distributions for the substrate emitting device. The definition of the angular coordinates \(\theta_x\) and \(\theta_y\) in the far-field are corresponding to \(x\)- and \(y\)-axis in Figure 1a. At low injection current of 33.0 A (Figure 5a), a small divergence far-field was obtained and the full width at half maximum (FWHM) of the main lobe emission cone is \(\theta_x \times \theta_y = 0.65^\circ \times 0.31^\circ\). At higher current levels (Figure 5b), an increased broadening of the main lobe (\(1.1^\circ \times 0.45^\circ\)) is observed due to more pronounced thermal effects especially for broad area laser related to self-focusing effect [28]. Figure 5c shows the 1D far-field in \(\theta_x\) direction derived from Figure 5a. The small dotted lines labeled TM\(_{00}\), TM\(_{03}\), and TM\(_{06}\) correspond to 1D fitting of the different order transverse far-field distribution. TM\(_{03}\) and TM\(_{06}\) is the third- and sixth-order transverse mode, respectively. In this direction, the far-fields exhibits hybrid transverse mode. Based on the measured 2D far-field intensity distributions (Figure 5a,b), we calculate the proportion of each transverse mode. At 33.0 A, TM\(_{00}\) weights with 35.7\%, TM\(_{03}\) 34.7\%, and TM\(_{06}\) 29.6\%. At 53.3 A, TM\(_{00}\) increased to 39.1\%, TM\(_{03}\) down to 32.7\%, and TM\(_{06}\) 28.2\%. In addition, we find that the whole electric field intensity distribution in \(\theta_x\) direction is slightly tilted by connecting a line of shoulder peak and main peak because the wave vector of \(a\) is oblique with \(a\) by an angle of \(80^\circ\). The emergence of TM\(_{03}\) and TM\(_{06}\) indicates that their losses are insufficient to suppress the gain. Figure 5d shows the 1D far-field in \(\theta_y\) direction.

![Figure 4](image-url)  
**Figure 4** Power versus current (I-L) characterization of a 4-mm-long CRPC substrate emitting QCL. With a ridge width of 390 \(\mu\)m at different heat sink temperatures between 10°C and 50°C. The inset shows the semilog plot of single-mode emission spectra at an injection current of 1.1A under pulsed mode operation, and a SMSR of 30 dB is maintained for the entire temperature range of 15°C to 65°C. Device edge facets were high-reflective coated, and substrate facets were anti-reflective coated.
derived from Figure 5a. The measurement far-field divergence angle in $\theta_y$ is much larger than diffraction-limited spreading angle 0.08°, which is mainly due to the real divergence angle which is too small for our measurement system to distinguish.

Mode competition in longitudinal and transverse direction strongly depends on driving the current [29]. In the far-field testing, we find an interesting phenomenon that the +2, +1, 0, −1, and −2 order beam peak intensities in $\theta x$ direction are changing in a certain manner as the injection current increases, where the 0 order position correspond to TM$_{00}$, and (+1, −1) pair corresponds to TM$_{03}$ and (+2, −2) TM$_{06}$. As shown in Figure 6, the 0 order and other high-order peak intensities increases as the driving current comes up to near 48 A. Then, the intensity of 0 order quickly rises to the maximum value as the driving current comes up to near 51.0 A. In contrast, +1 and −1 orders fall down to a low value while +2 and −2 orders jump up to a high value directly at the moment. This qualitatively reveals a transverse mode competition that TM$_{03}$ is suppressed. Subsequently when the current continues to increase beyond 51.0 A, the TM$_{00}$ begins to be weakened and the transverse far-field in $\theta x$ direction exhibits a strong tendency towards higher mode distribution.

The left inset of Figure 6 shows the lasing spectra under pulsed operation at different current from 1.05 $I_{th}$ to 2.1$I_{th}$. The tested laser shows single longitudinal mode operation at low injection current level. When the injection current increases, the FWHM of spectrum widens from 0.44 cm$^{-1}$ (29.6 A) to 1.16 cm$^{-1}$ (44.6 A), and even multi-wavelength lasing (>46.0 A). This may be due to the nonuniform refractive index of 2D photonic-crystal DFB grating, resulting from inherent linear Gaussian-like distribution of heat in the active region, giving rise to a longitudinal inhomogeneous gain profile of different spectrum. It is much more obvious for a

Figure 5 Measured far-field intensity distributions for the substrate emitting device. (a) 2D far-field intensity distribution under pulsed driving current of 33.0 A. (b) 53.3 A. (c) Measured 1D far-fields for $\theta x$ correspond to (a) and (b) for comparison. Simulated results of TM$_{00}$, TM$_{03}$, and TM$_{06}$ are depicted using dotted lines (d) 1D far-fields for $\theta y$.

Figure 6 Intensity for +2, +1, 0, −1, and −2 order beam peaks under various injection current. From 1.05$I_{th}$ to 2.1$I_{th}$ at room temperature. Inset: Spectra of the CRPC substrate emitting QCL under an increased injection current from 29.6 to 60.8 A.
broad area device to suffer spectrum widening since the operation current is so high that more electric energy transform into heat. In the future, when a shorter pulsed width source is applied for the drive of QCLs, the single longitudinal mode emission may persist to a higher operating current.

Conclusions

In conclusion, we report a high power and small divergence substrate emitting centered rectangular photonic-crystal quantum cascade laser. A record maximum peak output power for vertical emitting QCLs exceeding 10 W is obtained. Divergence far-field angle below 1° (0.65° × 0.31°) for QCLs is first realized. And the main lobe of far-field occupies approximately 40% of output energy. The laser shows a strong single longitudinal mode operation around 4.73 μm with SMSR of 30 dB even at high temperature.

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