# External Cavity Tuning of Coherent Quantum Cascade Laser Array Emitting at ∼7.6 µm *

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*An external cavity quantum cascade laser (QCL) array with a wide tuning range and high output power is presented. The coherent QCL array combined with a diffraction grating and gold mirror is tuned in the Littrow configuration. Taking advantage of the single-lobed fundamental supermode far-field pattern, the tuning capability of 30.6 cm$^{-1}$ is achieved with a fixed injected current of 3.5 A at room temperature. Single-mode emission can be observed in the entire process. The maximum single-mode output power of the external cavity setup is as high as 25 mW and is essential in real applications.*

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Quantum cascade lasers (QCLs) are extremely useful sources in the mid-infrared and terahertz regime and have been established as the most practical coherent source in many applications such as trace-gas sensing, free space communications and infrared spectrometer.[1−3] In these cases, single-mode emission is highly desirable. With the development of distributed feedback (DFB) QCLs, stable single-mode emission with high power and narrow divergence angles can be easily obtained at room temperature.[4−6] The main disadvantage of DFB QCLs is their limited tuning capability. Due to the strong mode selectivity of DFB gratings, the tuning range of these devices is restricted to only several cm$^{-1}$. Many attempts have been tried to broaden the tuning range of DFB QCLs.[7−11] Among these solutions, external cavity (EC) QCL is an effective way to obtain both wide tuning range and single-mode emission. Since its first demonstration in 2001,[12] tremendous progess on tunable width has been acquired. Specifically, Hugi *et al.*[13] and Bandyopadhyay *et al.*[14] reported a tuning range of over 432 cm$^{-1}$ and 1000 cm$^{-1}$ with a heterogeneous broadband active region, respectively. Although the broad tuning range can be obtained, the output power of EC-QCL is still restricted and should be increased for practice reasons. The most direct way to increase the output power of EC-QCL is using broad area devices as the gain media. These devices can supply more power by widening the ridge. However, simply increasing the ridge width beyond a certain value would result in the generation of high-order transverse modes. This will lead to the poor performance of single-mode operation and will limit the tunability of external cavity systems. Compared with broad area devices, properly designed coherent QCL arrays can present fundamental supermode far-field while supplying the high output power. This advantage shows great potential to increase the output power of external cavity systems. Recently, Raphael *et al.* designed an external cavity coherent QCL array and obtained a tuning range of 19.5 cm$^{-1}$ by rotating the grating at a fixed current.[15] The device they used presented a two-lobed far-field distribution. One lobe was used as output and the other was used as feedback. Thus the output power was reduced and the tunability was weakened due to the limited feedback power. According to our recent research, a coupled ridge waveguide coherent QCL array was first fabricated and a fundamental supermode far-field profile was obtained at a high injected current.[16] This device is very suitable to apply in external cavity systems, and a wider tuning range and higher output power can be expected due to its fundamental supermode far-field distribution.

In this Letter, we report an external cavity coherent QCL array emitting at ∼7.6 µm in the Littrow configuration. Taking advantage of the single-lobed far-field distribution, a wide tuning range of 30.6 cm$^{-1}$

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is obtained at a fixed injected current of 3.5 A. Single-mode emission can be observed in the entire process. The output power around central frequency is as high as 25 mW. Since both of the facets of the device are uncoated, the tuning capability, such as the tuning bandwidth and precision, should be further improved by use of anti-reflection (AR) coating on the front facet of the chip.[17–19]

The QCL array adapted in this experiment, consisting of 5 elements in parallel with stripe width $W = 6\,\mu\text{m}$ and etched interspace $S = 6\,\mu\text{m}$, is designed to emit at around 7.6 μm. Before actually manufacturing, simulation was carried out with the finite element method software (COMSOL). The simulation results are shown in Fig. 1. When the injected current is increased above the threshold value, the array ridges and interspaces present gain instead of loss, and the gain of the interspaces is even larger than that of the ridges. Under this condition, the fundamental supermode has higher modal gain than any other supermodes and a single-lobed far-field is favored.[20] Near-field distribution is shown in Fig. 1(a), which clearly indicates the fundamental supermode operation. As shown in Fig. 1(b), a single-lobed far-field distribution with a divergence angle of 7.6° is obtained, which matches the experimental data well.

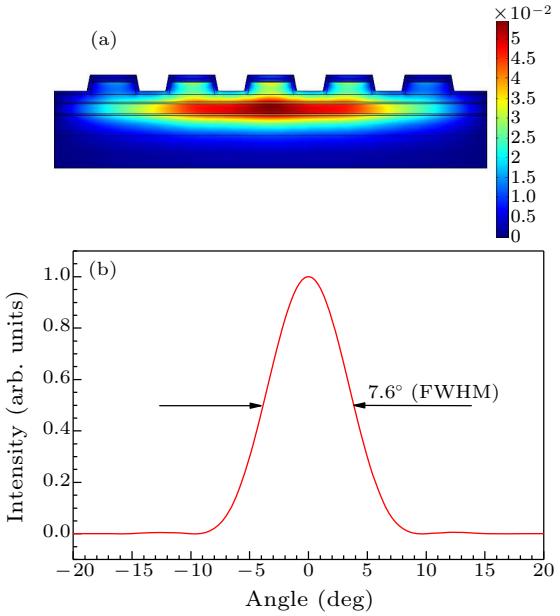


**Fig. 1.** (a) The near-field distribution of the device. (b) The calculated far-field angle according to the near-field distribution.

The actual device structure is shown in Fig. 2(a). The active region is based on the double-phonon resonant design, and consists of strain-compensated $In_{0.6}Ga_{0.4}As/In_{0.4}Al_{0.6}As$ layers, which is similar to that described in Ref. [21]. Following the completion of material growth, the wafer was etched into the coupled ridge waveguide structure with a depth of 2.5 μm by wet chemical etching. Compared with the upper InP cladding layer thickness of 3.5 μm, the etching depth of 2.5 μm means the completeness of active region in the etched area. Then a 450-nm-thick $SiO_2$ was deposited by chemical vapor deposition (CVD) for insulation. Electrical contact was provided by a Ti/Au layer. To improve the heat dissipation, a 4-μm-thick gold layer was electroplated on the Ti/Au layer. After thinning the substrate down to 160 μm, a Ge/Au/Ni/Au metal contact layer was deposited on the back side of the sample. The cavity of the QCL array was cleaved to be 2 mm in length and both of the facets were uncoated. The laser arrays were bonded episide-down on SiC submounts with indium solder and then mounted on copper heat sinks for better heat dissipation. This device could only work in the pulsed mode and was tested with a pulse width of 1 μs and repeat frequency of 10 kHz at room temperature. The spectrum of the coherent QCL array is a typical Fabry–Pérot (FP) mode with a mode spacing of $0.72\,\text{cm}^{-1}$. The central frequency is around $1311\,\text{cm}^{-1}$, corresponding to a wavelength of 7.63 μm. The main advantage of this device is its single-lobed fundamental supermode far-field profile with a narrow divergence angle, as shown in Fig. 2(b). When the injected current was increased from 4 A to 7 A, the divergence angle was enlarged slightly from 7.4° to 9.2°, and the far-field remained single-lobed emission with a symmetric Gaussian profile.

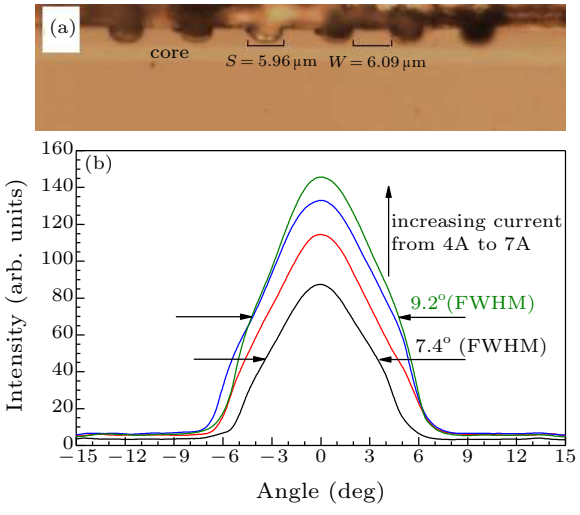


**Fig. 2.** (a) Microscope image of the device facet, and (b) the far-field distribution of the coherent QCL array.

The coherent QCL array was further collimated for external cavity feedback by an AR-coated aspheric lens (Lightpath Technologies, 390037) fixed at a 3-axis adjusted platform. Then a plane ruled reflectance grating blazed at 7.4 μm (165 groove/mm, diffraction efficiency ∼80%) and a gold flat mirror, both fixed at a step motor controlled rotation stage with 0.01° resolution, were put in front of the laser source in parallel

to constitute a Littrow configuration. Thus the first-order diffraction of the grating was selected as feedback light and the zeroth-order diffraction of the grating was emitted as output light through the reflection of the gold mirror. The grating grooves were oriented perpendicular to the laser polarization plane to obtain better diffraction efficiency. The distance between the QCL array and the diffusion grating was about 10 cm. The wavelength tuning of the external cavity setup was based on the grating equation, $2d\sin(\theta) = m\lambda$, where $d$ is the distance between grooves of the grating, $\theta$ is the incident angle of the beam, $m$ is the diffraction order, and $\lambda$ is the emission wavelength of the external cavity. For the Littrow configuration, the diffraction order $m = 1$ and the feedback wavelength of the output beam is determined by the incident angle $\theta$ and is tuned by rotating the grating.

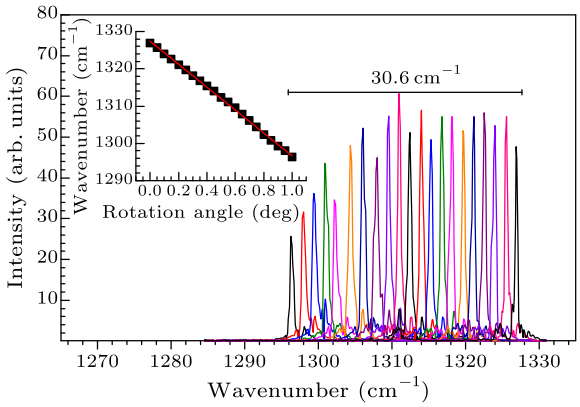


**Fig. 3.** The tuning spectra of the external cavity coherent QCL array. The inset shows the good tuning linearity of this setup. The fitted tuning coefficient is $-30.73\,\mathrm{cm}^{-1}$/degree.

The spectra measurement was carried out by a Fourier-transform infrared spectrometer with a resolution of $0.25\,\mathrm{cm}^{-1}$ (Thermo Fisher Scientific, Nicolet 8700). The external cavity coherent QCL array can work in the pulsed mode at room temperature. The driving current was fixed at 3.5 A with a pulse width of 1 µs and a repeat frequency of 10 kHz. To avoid the effect of temperature shift, a thermo-electric cooler (TEC) was hired to stabilize the temperature at 25℃. Thus the wavelength was only controlled by the tuning angle of the diffraction grating. Rotating the grating allowed only discrete tuning on the FP modes of the gain element separated by $1/2n_gL$, where $n_g$ is the effective refractive index of wafer, and $L$ is the length of chip. Assuming $n_g = 3.2$, for a 2 mm cavity length, the FP mode-space is about $0.78\,\mathrm{cm}^{-1}$ (∼4.5 nm). The free spectral range (FSR) of the tuning filter is FSR=$2p\Delta\alpha\cos(\alpha)$, where the grating pitch $p = 1/165$ mm, the sweep angle $\Delta\alpha = 0.05°$, and the incident angle at central frequency $\alpha = 38.95°$. The calculated FSR is ∼8.2 nm, which is larger than the FP mode-space. Since the mode-spacing of the external cavity laser is decided by the FP own modes, we can secure a tunable spectrum when the grating angle is rotating. Fine tuning can be achieved by varying simultaneously the grating angle with smaller step and the injected current or the heat-sink temperature. Taking advantage of the wave selection characteristic of the grating, when the incident angle is set, only specified longitudinal mode can be selected as feedback and be magnified and other modes of FP cavity are suppressed. Thus single-mode emission can be obtained due to the role of grating. To obtain the entire tuning range, a step angle of 0.05° was adopted from the initial incident angle of 38.45°, the right beginning of the external cavity mode and corresponding to a frequency of $1326.95\,\mathrm{cm}^{-1}$. When the incident angle was increased to 39.45°, corresponding to a frequency of $1296.30\,\mathrm{cm}^{-1}$, the external cavity mode was tuned to the spectra extreme. A total tuning range of $30.6\,\mathrm{cm}^{-1}$ was obtained with a good tuning linearity, as shown in Fig. 2. The fitted tuning coefficient was $-30.73\,\mathrm{cm}^{-1}$/degree. A wider tuning range can be expected by depositing an AR coating on the front facet of the chip, since it can suppress the FP modes inside the QCL cavity while increasing the feedback to the QCL chip,[17–19] and then the tuning precision is decided by the external cavity mode separated $1/2(n_gL + L_{\mathrm{external}}) \sim 0.05\,\mathrm{cm}^{-1}$.

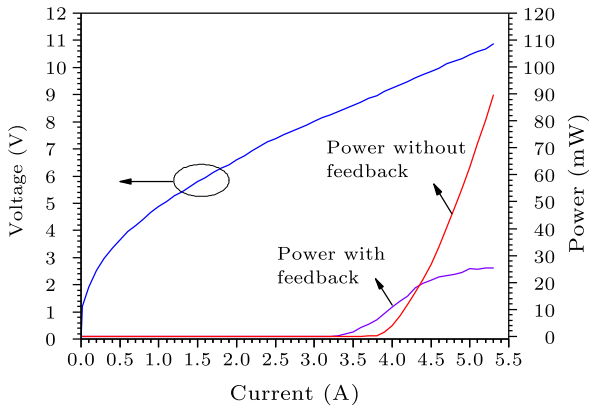


**Fig. 4.** Light-current curve of the external cavity setup. The red line represents the output power without feedback and the purple line represents the power with feedback. The blue line shows the voltage–current characteristics.

After spectra measurement, the output power of the external cavity setup was measured by a calibrated thermopile detector (Coherent, EPM1000). As shown in Fig. 4, the maximum output power with feedback is 25 mW around the central frequency. However, the power without feedback in the FP cavity laser is as high as 90 mW. The power ratio of EC-QCL and FP-QCL is 27.8%. This is because the emitted light of the EC-QCL was collected from the zeroth-order diffraction of the grating and the diffraction efficiency of the

zeroth-order is very low.[11] The low power of the device is also inherently limited by the material quality and a higher power can be expected when a better wafer is used.

In conclusion, we have developed an EC-QCL array setup and obtained a wide tuning range of $30.6\,\mathrm{cm}^{-1}$ with a linear tuning coefficient of $-30.73\,\mathrm{cm}^{-1}$/degree by utilizing the single-lobed far field of the laser source. Single-mode emission can be observed in the entire process. The maximum single-mode power around central frequency is as high as 25 mW. A wider tuning range and higher output power can be expected by use of AR coating on the front facet of the chip.

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