Spectral beam combining of discrete quantum cascade lasers

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Abstract
In this paper, we report a spectral beam combining technique based on discrete quantum cascade lasers at λ ~ 4.8 μm. Good beam qualities of $M^2 < 1.3$ for both fast and slow axes are obtained. The entire spectrum span is approximately 29.1 cm$^{-1}$, which is consistent with the theoretical results of grating equation. Maximum beam combining efficiency of 58.9% with output power exceeding 1 W is demonstrated under continuous wave operation at room temperature. The limit of beam combining efficiency is theoretically investigated. The independent temperature control for the discrete lasers circumvented the issue of thermal crosstalk between the lasers on an array and pave the way to high power and high efficiency laser spectral beam combining.

Keywords Quantum cascade laser (QCL) · Spectral beam combining (SBC) · High power output

1 Introduction

Since the first demonstration, quantum cascade laser (QCL) (Faist et al. 1994) has been made tremendous progress. Its emitting wavelength is widely tailorable, covering as short as 3 μm in the mid-infrared range (Devenson et al. 2007; Zhang et al. 2009), and as long as 300 μm in the terahertz domain (Kohler et al. 2003). Up to now, in continuous wave (CW) mode QCLs have been realized emitting more than 5 W of output power at room temperature (Lu et al. 2020). Nevertheless, much higher power mid-to-far infrared output will be advantageous for applications like remote sensing and countermeasure.

Limited by the slow development of energy band design to increase power, beam combining is apparently the next step to further enhance the optical power. Beam combining can be divided into two categories, one is coherent beam combining and the other is...
incoherent beam combining. The coherent beam combining based on Michelson cavity (Bloom et al. 2010) and Dammann grating (Bloom et al. 2011) usually leads to a high beam combining efficiency and good beam quality, however, a complicated optical structure or grating (Dammann grating was fabricated with complicated processes) is always needed. The phase mismatch and power modulation between the beams also make the beam alignment rather difficult. Incoherent beam combining of lasers, on the other hand, has been widely investigated, such as wavelength beam combining of DFB array with a grating (Lee et al. 2009), hollow waveguide beam combining (Elder et al. 2012), spatial beam combining (Wu et al. 2013), and spectral beam combining (SBC) (Hugger et al. 2009, 2010; Daneu et al. 2000). Among them, SBC is an effective technique to achieve high output power with good beam propagation characteristics close to that of a single emitter. Relying on the wavelength-dependent diffraction by a grating (or a dispersive element), SBC can achieve total power amplification in a certain spectral region without deteriorating the beam quality.

Currently, the SBC of QCLs is mainly realized by the chip-based laser array (Hugger et al. 2009, 2010). In this way, spectral beam combining of up to eight individual QC lasers is achieved with an optical coupling efficiency of 60% for an array of six emitters. The resulting beam quality (M2 < 2 for both fast and slow axes) is close to that observed for single emitters. From the perspective of dealing with heat transfer for lasers with high injection power density, the typical SBC of QCLs array reported in the literature only works in the pulse modes. CW operation was not demonstrated for SBC of QCLs due to the excessive thermal load and thermal crosstalk between the lasers.

In this work, we introduced an SBC technique based on discrete QCLs, aligned by aspherical lenses combined with a telephoto lens. In principle, SBC based on discrete QCLs with an independent cooling module is more efficient to achieve high CW power. In this scenario, the output power of the individual laser chips can be optimized to maximize the total power via the grating diffraction beam combining.

Taking four single-tube Fabry–Perot (FP) QCLs with a wavelength of ~4.8 μm as an example, the beam combining efficiency at the maximum output power above 1 W is demonstrated to be 58.9%, and the theoretical limit of the beam combining efficiency is analyzed and estimated based on the slope efficiency of lasers, which is close to the experimental results. High beam quality is achieved, the fast and slow axis directions after beam combination are 1.26 and 1.29, respectively.

2 Spectral beam combining setup

Different from the SBC of QCL array on a chip (Hugger et al. 2009, Hugger et al. 2010), the beam combining setup in this work uses a large aperture telephoto transform lens to focus the collimated beams from discrete QCLs onto a point on a diffraction grating for beam combining. The diagram of the spectral combining of discrete QCLs is shown in Fig. 1. A collinear output beam is generated when the emission wavelength of each laser is chosen and determined by the first-order diffraction grating, as shown in the grating equation.

\[
\sin \alpha + \sin \beta = \lambda / g
\]

where \(\alpha\) denotes the angle of incidence relative to the grating normal given by the lateral position of the emitter, \(\beta\) is the diffraction angle, and \(g\) the grating period. The lateral offset
Δx relative to the central emitter with the angle of incidence α₀ has to be compensated to first order by a wavelength shift of Δλ = g Δxf cos α₀ (Hugger et al. 2009, 2010).

The transform lens with a proper focus length is the key to success. A simple method can be used to estimate the focal length before the experiment. Based on our experience, the effective grating rotation angle θ in the Littrow external cavity configuration is generally less than 2°. The tangent of this angle θ should be approximately equal to the ratio of the maximum beam spacing X to the focal length f, shown in Fig. 1. Eventually, the focal length should be greater than the value of X/tan(θ) to ensure that all lasers can form external cavity feedback within a range of fewer than 2°.

The QCL wafer was grown on an n-doped InP substrate by solid-source molecular beam epitaxy (MBE). After growth, the ridge was processed by conventional photolithography and a nonselective wet chemical etching. A buried heterogeneous (BH) structure was introduced into this device: Semi-insulated InP:Fe with high thermal conductivity was grown on both sides of the ridge through selective epitaxy by metal–organic vapor phase epitaxy (MOVPE). The four QCLs used the same waveguide dimensions with a width of 8um and a length of 5 mm. The front facets were anti-reflection coated with 400 nm Al₂O₃ (R ~ 16%), while a high-reflection coating was applied to the back facets with Al₂O₃/Ti/Au/Ti/Al₂O₃. To further improve the heat dissipation and achieve higher power output, the device was epi-side-down mounted on the diamond heatsink with indium. After installing the thermistor, the laser was fixed on the water cooling platform with a thermoelectric cooler (TEC) for temperature control. Four FP QCLs are collimated by aspherical lenses from Lightpath (f= 1.87 mm, NA = 0.85). Three 5 mm * 5 mm low-loss gold-coated mirrors are used to adjust the beams to make them compact parallel output. The final lateral offset between the nearest neighbor beams is 4.1, 4.5, 4.4 mm, respectively. In this experiment, the maximum spacing of the parallel beams is about 13 mm. Following the above estimation, the focal length of the transfer lens should be greater than 372 mm. Thus a lens with a focal length of 500 mm is selected as the transform lens from Thorlabs (MgF₂ Plano-Convex Lens, T > 96.2% @ ~4.8um). A half-wave plate is inserted into the grating and transform lens for rotating the polarization by 90°. Then the maximum grating (300 lines/mm, 41°) diffraction efficiency can be obtained. Finally, a coated Ge plate is used as an output coupler with a Fresnel reflection of ~30%.
3 Experimental results and analysis

The combining efficiency is an important index to evaluate the combination system, defined as the ratio of the total optical power after combining to the sum of optical power before SBC (Zhu et al. 2016). The performances of four discrete QCLs are measured at the heat sink’s temperature of 25 °C in CW mode, respectively. The typical power-current-voltage (P-I-V) curves of each QCLs before SBC are shown in Fig. 2a. The slope efficiency of the four lasers is basically the same with the value of 1.67 W/A. The difference in laser threshold current is mainly caused by the device process. Figure 2b shows the total power and the combining efficiency after SBC. Since the optical feedback changes the lasing threshold and the slope efficiency of the laser, as the injection current increases, the efficiency of spectral beam combining decreases. When the power of each laser is 0.45 W, the total power after beam combination exceeds 1 W, and the corresponding beam combining efficiency is 58.9%.

The theoretical beam combining efficiency helps to evaluate the experimental results. To further understand the SBC process, the experiment can be understood as four Littman external cavity configurations. The beam combining efficiency is approximately equal to the external cavity efficiency of a single laser, which is expressed as the power ratio of the FP laser to the external cavity laser.

For FP lasers and external cavity lasers, from laser lasing to saturation output, the output power and current are approximately linearly related to

\[ P = \eta_s (I - I_{th}) \]

where \( P \) is the output power, \( I \) is the applied current, and \( I_{th} \) is the threshold current. \( \eta_s \) is the slope efficiency. Then the beam combining efficiency defined as the power ratio of the laser before and after the external cavity can be expressed as

\[
\frac{P_E}{P_F} = \frac{\eta_{s,E} (I - I_{th,E})}{\eta_{s,F} (I - I_{th,F})}
\]

where \( P, I, I_{th} \) represent the optical power, the applied current, and the threshold current. The subscripts F and E indicate the value before and after the external cavity, respectively (same below). The slope efficiency \( \eta_s \) can be expressed as \( \eta_s = \eta_i \frac{h \nu N_s}{e} (\alpha_m + \alpha_w) \), \( \eta_i \) is the internal quantum efficiency, \( h \nu \) is the photon energy, \( N_s \) is the number of stages, \( e \) is the electron charge and \( \alpha_w \) is the waveguide loss originating outside the laser gain medium. The cavity mirror loss \( (\alpha_m) \) is defined by

![Fig. 2 a P-I-V of four Fabry–Perot QCLs. b Left, total optical power after SBC versus optical power of each laser. Right, combining efficiency versus optical power of each laser](image)
where $L$ is the cavity length, $R_f = 0.16$ and $R_b \approx 1$ are the reflectivities of the front and back facet of lasers, respectively. In the external cavity system, the front facet and the external components are regarded as an effective front facet as shown in Fig. 3. The reflectivity of the effective front facet is estimated by

$$R_{fE} = R_f + \left(1 - R_f\right)T_e T_{0.5} D_g R_{oc} D_g T_{0.5} T_e \left(1 - R_f\right) + R > 1,$$

where $(1 - R_f)T_e T_{0.5} D_g R_{oc} D_g T_{0.5} T_e \left(1 - R_f\right)$ represents the reflectivity of the light that is first fed back into the chip by the output coupler. The reflectivity caused by the output coupler in the second time is only about 0.03 times the first time, so the reflectivity ($R_{>1}$) of more than one time feedback process is ignored in the calculation. The transmittance $T_e$ of the collimating lens is about 98%, the transmittance $T_t$ of the transform lens is greater than 96%, and the transmittance $T_{0.5}$ of the half-wave plate is about 99%. $\eta_g$ is the diffraction efficiency of the grating is greater than 92%, the reflectivity of output coupler $R_{oc}$ is about 30%.

Near room temperature, the transparent current density ($J_{tr}$) is negligible (Yu et al. 2008). Then the threshold current density ($J_{th}$) can be approximated as follows.

$$J_{th} = J_{tr} + \frac{(\alpha_m + \alpha_w)}{g \Gamma} \approx \frac{(\alpha_m + \alpha_w)}{g \Gamma}$$

where $g$ is the gain coefficient, and $\Gamma$ is the optical confinement factor within the active waveguide core. When considering the efficiency near saturation, the threshold change before and after the external cavity is small. Finally, the beam combining efficiency can be approximated as follows when the threshold change was ignored.

$$P_{E} = \frac{\alpha_m}{\alpha_m + \alpha_w} \cdot \frac{(\alpha_m + \alpha_w)}{g \Gamma} \approx \frac{1}{2L} \ln \left(\frac{1}{R_{fE} R_b}\right) \cdot J_{thE} \approx 62.8\%$$

The experimental results 58.9% are roughly consistent with the theoretical value. The slightly larger theoretical value mainly comes from some approximations, including the lack of consideration of light loss, multiple feedback processes, etc. Based on the above theory, it is also helpful to guide the design and analysis the effect of laser coating.

The lasing spectrum after the external cavity SBC was measured with a Fourier transform infrared (FTIR) spectrometer in rapid scan mode with a resolution of 0.25 cm$^{-1}$. To avoid laser damage, all four lasers were used in the limited CW output power of 0.4 W. The wavelength distribution after SBC is recorded as shown in Fig. 4. Four discrete single wavelengths with basically the same intensity were observed. Referring to the SBC structure, each wavelength corresponds to one laser, which means that all four QCLs are perfectly locked in wavelength. The adjacent wavenumber intervals are 9.8,
10, and 9.9 cm\(^{-1}\), respectively. The entire spectrum span is approximately 29.1 cm\(^{-1}\), which is consistent with the theoretical results of the grating equation.

The beam quality factor \(M^2\) is the accepted standard for characterizing the general performance of a laser beam. The beam pictures at different positions were recorded with attenuation by Pyrocam IV beam profiling camera (Ophir photonics) after focusing by an objective with a focal length of 250 mm under the condition of 1 W output power. The Knife Edge 10/90 method (Nemoto 1992), employing a fixed 10 and 90% of energy as the moving edge clip points, is used to determine the spot size of the beam pictures. The collected data of the spot size is fit to the hyperbolic beam propagation equation,

\[
W(z)^2 = W_0^2 + \Theta^2(z-z_0)^2,
\]

the results of the fit yield values for \(W_0\), \(\Theta\), and \(z_0\) in both the X and Y axes of beam width, shown in Fig. 5. The \(M^2\) is computed from the values obtained from the curve fit as,

\[
M^2 = \frac{W_0\Theta\pi n}{4\lambda},
\]

where \(\lambda\) is the laser wavelength at vacuum, \(n\) is the index of refraction of the medium. The \(M^2\) in the slow and fast axis, corresponding to the data X and Y in Fig. 5, are 1.29 and 1.26, respectively. The experimental result is almost the same as the beam quality of a single emitter in both Fig. 5  Beam quality measurement of QCLs after SBC. The red and blue data points are the sizes of the fast and slow axis directions at different positions. The fitted curves correspond to the solid lines of the same color. The final \(M^2\) in the fast and slow axis directions are 1.26 and 1.29 respectively. The inset shows the spot pattern at a distance of 580 mm from the lens.
directions. This shows that the four lasers still have good beam propagation characteristics after SBC.

4 Conclusion

In summary, we have demonstrated the external cavity spectral beam combining of a four-tube FP QCLs with the watt-level output power under CW operation at room temperature. The beam combining efficiency of 58.9% with $M^2_x$ of 1.29 and $M^2_y$ of 1.26 was obtained, respectively. Based on the slope efficiency, the theoretical efficiency of the SBC system is estimated to be 62.8%. This method is helpful to provide guidance for the selection of optical components. In the future, the transform lens will be replaced by mirrors to achieve module miniaturization, which is more convenient to application.

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