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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 $\lambda \sim 4.8 \mu\text{m}$. 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.

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1 Introduction

Since the first demonstration, quantum cascade laser (QCL) ¹ has been made tremendous progress. Its emitting wavelength is widely tailorable, covering as short as $3 \mu\text{m}$ in the mid-infrared range ², ³, and as long as $300 \mu\text{m}$ in the terahertz domain ⁴. Up to now, in continuous wave (CW) mode QCLs have been realized emitting more than 5 W of output power at room temperature ⁵. Nevertheless, much higher power mid-to-far infrared output will be advantageous for applications like remote sensing and countermeasure. Since the individual QCL chip is approaching its power limit in CW operation, 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 ⁶ and Dammann grating ⁷ 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 makes 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 grating⁸, hollow waveguide beam combining⁹, spatial beam combining¹⁰, and spectral beam combining (SBC)¹¹⁻¹³. 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 array¹¹⁻¹². 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 $\sim 4.8\mu\text{m}$ as an example, the beam combining efficiency at the maximum output power above 1W 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

Fig. 1 Schematic diagram of spectral beam combining (SBC) experiment. CL, collimating lens; TL, transform lens; $\frac{1}{2} \lambda$, half-wave plate; DG, diffraction grating; OC, output coupler.

Different from the SBC of QCL array on a chip¹¹⁻¹², 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 α denotes the angle of incidence relative to the grating normal given by the lateral position of the emitter, β is the diffraction angle, and g the grating period. The lateral offset Δx relative to the central emitter with the angle of incidence α_0 has to be compensated to first order by a wavelength shift of $\Delta \lambda = g \Delta x / f \cos \alpha_0$.¹¹⁻¹²

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 degrees. 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 $X/\tan(\theta)$ to ensure that all lasers can form external cavity feedback within a range of fewer than 2 degrees.

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 8 μ m and a length of 5mm. The front facets were anti-reflection coated with 400nm Al_2O_3 ($R \sim 16\%$), while a high-reflection coating was applied to the back facets with $\text{Al}_2\text{O}_3/\text{Ti}/\text{Au}/\text{Ti}/\text{Al}_2\text{O}_3$. 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 ($f=1.87\text{mm}$, $\text{NA}=0.85$). Three 5mm*5mm 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 4.1mm, 4.5mm, 4.4mm, respectively. In this experiment, the maximum spacing of the parallel beams is about 13mm. Following the above estimation, the focal length of the transfer lens should be greater than 372mm. Thus a lens with a focal length of 500mm is selected as the transform lens from Thorlabs (MgF_2 Plano-Convex Lens, $T > 96.2\% @ \sim 4.8\mu\text{m}$). 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 $\sim 30\%$.

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 SBC¹⁴. 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. 2(a). The slope efficiency of the four lasers is basically the same with the value of 1.67W/A. The difference in laser threshold current is mainly caused by the device process. Fig. 2(b) shows the total power and the combining efficiency after SBC. With the increase of electrical injection current, the influence of optical feedback on the overall output power is reduced, then the SBC efficiency decreases. When the power of each laser is 0.45W, the total power after beam combination exceeds 1W, and the corresponding beam combining efficiency is 58.9%.

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.

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 I_{th} is the threshold current, η_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 η_s can be expressed as $(\eta_i h\nu N_s \alpha_m)/e/(\alpha_m + \alpha_w)$, η_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 α_w is the waveguide loss originating outside the laser gain medium. The cavity mirror loss (α_m) is defined by

$$\alpha_m = \frac{1}{2L} \ln \left(\frac{1}{R_f R_b} \right)$$

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 $R_{fE} = R_f + (1 - R_f) T_c T_t T_{0.5} D_g R_{oc} D_g T_{0.5} T_t T_c (1 - R_f) + R_{>1}$, where $(1 - R_f) T_c T_t T_{0.5} D_g R_{oc} D_g T_{0.5} T_t T_c (1 - R_f)$ 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_c 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%. η_g is the diffraction efficiency of the grating is greater than 92%, the reflectivity of output coupler R_{oc} is about 30%.

Fig. 3 Schematic diagram of the effective front facet.

Near room temperature, the transparent current density (J_{tr}) is negligible¹⁵. 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 Γ 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.

$$\frac{P_E}{P_F} = \frac{\alpha_{m_E}}{\alpha_{m_F}} \cdot \frac{(\alpha_{m_F} + \alpha_{w_F})}{(\alpha_{m_E} + \alpha_{w_E})} \approx \frac{\frac{1}{2L} \ln\left(\frac{1}{R_f R_b}\right)}{\frac{1}{2L} \ln\left(\frac{1}{R_f R_b}\right)} \cdot \frac{J_{th_F}}{J_{th_E}} \approx 62.8\%$$

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 0.4W. 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 9.8cm^{-1} , 10cm^{-1} , and 9.9cm^{-1} , respectively. The entire spectrum span is approximately 29.1 cm^{-1} , which is consistent with the theoretical results of the grating equation.

Fig. 4 Wavelength distribution after SBC of four QCLs. There is a corresponding relationship between the spectral interval and the laser arrangement pitch, which satisfies 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 250mm under the condition of 1W output power. The Knife Edge 10/90 method¹⁶, 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 , Θ , 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, $M^2 = W_0^2 \Theta \pi / 4 \lambda$, where λ 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 X and Y axis in Fig. 4, are 1.29 and 1.26, respectively. The experimental result is almost the same as the beam quality of a single emitter in both directions. This shows that the four lasers still have good beam propagation characteristics after SBC.

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 580mm from the lens.

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_x^2 of 1.29 and M_y^2 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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Caption List

Fig. 1 Schematic diagram of spectral beam combining (SBC) experiment. CL, collimating lens; TL, transform lens;
 $\frac{1}{2}\lambda$, half-wave plate; DG, diffraction grating; OC, output coupler.

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.

Fig. 3 Schematic diagram of the effective front facet.

Fig. 4 Wavelength distribution after SBC of four QCLs. There is a corresponding relationship between the spectral
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580mm from the lens.

Figures

Figure 1

Schematic diagram of spectral beam combining (SBC) experiment.

Figure 2

(a) P-I-V of four Fabry-Pérot QCLs. (b) Left, total optical power after SBC versus optical power of each laser. Right, combining efficiency versus optical power of each laser.

Figure 3

Schematic diagram of the effective front facet.

Figure 4

Wavelength distribution after SBC of four QCLs. There is a corresponding relationship between the spectral interval and the laser arrangement pitch, which satisfies the grating equation.

Figure 5

Beam quality measurement of QCLs after SBC.