Research Article | Vol. 30, No. 2 / 17 Jan 2022 / Optics Express 966
Optics EXPRESS

Dense spectral beam combining of quantum cascade lasers by multiplexing a pair of blazed gratings

JUN ZHANG,[1,2] HANGYU PENG,[1,2,*] JINGBO WANG,[1,2] JIYE ZHANG,[1,2] LI QIN,[1,2] YONGQING NING,[1,2] AND LIJUN WANG[1,2]

[1] *State Key laboratory of Luminescence and Application, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China*
[2] *Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China*
[*] *penghy@ciomp.ac.cn*

Abstract: A method of compressing spectral bandwidth in spectral beam combining (SBC) of quantum cascade lasers (QCLs) by multiplexing a pair of blazed gratings arranged in a V-shaped configuration is proposed. The spectral interval can be compressed by increasing the number of diffractions via the round-trip propagation between gratings. Experimental results show that the SBC spectral interval of three diffractions is narrowed to 1/3 that of a single diffraction. The SBC power can be further improved within a given spectrum range by increasing the number of QCLs, which provides a feasible scheme to scale the SBC power and the brightness of QCLs.

1. Introduction

Quantum cascade lasers (QCLs) are semiconductor lasers that directly lase the mid-infrared (MIR) laser from 3 µm to 300 µm by using electric drive only. They are ideal components for gas sensing, environmental monitoring, medical diagnosis, and defense, due to their simplicity of operation, high efficiency and small size [1–2]. Such applications require the necessary power, beam quality, and reliability [3]. QCLs have been achieved watt-level output power in continuous wave (CW) mode at room temperature for many years. The highest CW power record of 5.1 W from a single QCL emitter was set in 2011 [4]. To obtain a higher output power with high beam quality, the technology of spectral beam combining (SBC) has been proven to be one of the most attractive and feasible ways to achieve power and brightness scaling by employing the grating dispersion [5]. S. Hugger et al. achieved SBC of eight individual QCLs with the wavelength from 4.5 µm to 5.0 µm, and the SBC beam quality of $M^2 < 2$ for both fast and slow axes was obtained, which was close to that observed for single emitters [6]. A. Goyal et al. demonstrated several types of SBC sources based on QCLs with different structures and different wavelengths from 8 µm to 10 µm [7–8]. An obvious way to achieve a higher power laser beam is by just combining more QCLs, besides improving the QCL power. However, SBC scales laser power and brightness at the expense of spectral bandwidth broadening. The whole spectral span of the SBC source will be broadened with the increase of the quantity of QCLs. Nevertheless, the number of QCLs cannot increase infinitely because of the finite spectral span, limited by the application requirements and the characteristics of laser unit or optical element. In order to increase the SBC power within a limited bandwidth, it is necessary to raise the number of the combing QCLs by compress the wavelength interval between adjacent laser units. A narrower wavelength interval indicates more amount of combining elements in the same spectral range, resulting in the promotion of the SBC power. The spectral bandwidth of SBC is inversely proportional to the grating dispersion [9]. According to the grating diffraction theory, the quantity of grating lines per mm in MIR is small, generally being 75-300 lines/mm, thus resulting in a low

#446124 https://doi.org/10.1364/OE.446124
Journal © 2022 Received 19 Oct 2021; revised 3 Dec 2021; accepted 19 Dec 2021; published 3 Jan 2022

Optics EXPRESS

dispersion of 0.1-0.4 mrad/nm. With a larger wavelength, fewer grating lines per mm indicate lower corresponding dispersion and larger spectral interval, leading to smaller amounts of QCLs that can be coupled within a given gain spectrum. Promoting the grating dispersion capability helps to compress the SBC spectral interval and the output power and brightness of SBC QCLs can be further improved by increasing the number of QCLs.

A method of dense spectral beam combining (DSBC) of QCLs by multiplexing a pair of blazed gratings arranged in a V-shaped configuration is proposed. A novel SBC structure in a modified Littman-Metcalf setup [10] with two blazed gratings for wavelength selective optical feedback is built. The dispersion capability is greatly improved by increasing the number of diffractions via the round-trip propagation between gratings, and the SBC spectrum of QCLs is effectively compressed. Experimental setups of SBC-QCLs with a single diffraction (1-SBC), double diffractions (2-SBC) and three diffractions (3-SBC) are built, composed of two QCLs and two gratings. The spectral interval is narrowed from 36.95 nm to 17.16 nm and 12.22 nm, with spectral compression ratios of 2.15 and 3.02 respectively, which is consistent with the theoretical analysis. The spectral interval can be further compressed only by adjusting the angle and position of the two reflective gratings to increase the diffraction times, without introducing any additional component.

2. Experimental setup

A standard SBC setup with a single diffractive grating [11] is shown in Fig. 1(a). A novel SBC configuration in a modified Littman-Metcalf setup with two blazed gratings for wavelength selective optical feedback is built, as shown in Figs. 1(b)–1(d). Two gratings are placed in a V-shaped configuration, and different numbers of diffractions can be achieved without introducing any additional component, being achieved only by adjusting the angle of θ_i, θ_d, θ_g, and the position of the two gratings. The SBC structures with double diffractions, three diffractions and six diffractions are modeled by Zemax.

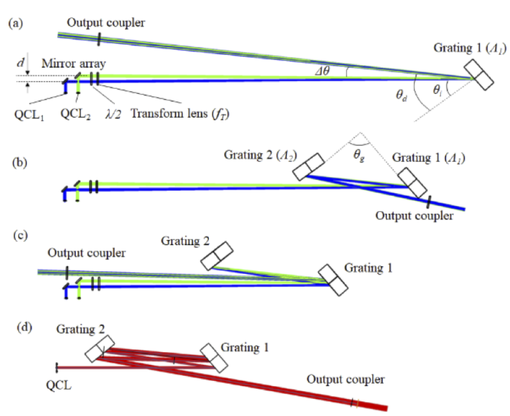

Fig. 1. Setup for SBC configuration with (a) a single diffraction, (b) double diffractions, (c) three diffractions and (d) six diffractions.

The resonant cavity is formed by the back facet of QCLs and the output coupler. The divergent beams emitted from QCLs are first collimated. Then the direction of each beam is deflected by 90 ° though the respective mirror, and the offset d can be adjusted. All beams are redirected by the transform lens (focal length f_T), and overlap on the last grating after several diffractions. Hence, the overlapped spot is on grating 1 for 1-SBC in Fig. 1(a), on grating 2 for 2-SBC in Fig. 1(b), back on grating 1 for 3-SBC in Fig. 1(c), and on grating 2 for 6-SBC in Fig. 1(d). Only the diffraction beams perpendicular to the output coupler are fed back into the QCLs to generate an effective resonance oscillation. Each QCL receives feedback signals with a unique wavelength induced by the different incident angle θ_i and the same diffraction angle θ_d on the gratings and emits a beam with a unique wavelength λ_i, $\lambda_i=\Lambda(sin\theta_i+sin\theta_d)$ for 1-SBC, in which Λ denotes the grating period. Finally, all beams are superposed at the output coupler and emitted as a broad spectrum $\Delta\lambda$ along the same direction, maintaining the beam quality of a single emitter while scaling the output power by the number of QCLs.

$\Delta\lambda$ can be deduced to $\Delta\lambda=(d\lambda/d\theta)*d/f_T$, inversely proportional to the grating dispersion $d\theta/d\lambda$. A large the dispersion $d\theta/d\lambda$ indicates a small spectral bandwidth $\Delta\lambda$. To achieve a high diffraction efficiency, the angle interval $\Delta\theta$ between θ_i and θ_d is as small as possible if the spatial structure allows. After N diffractions, the corresponding dispersion $d\theta_N/d\lambda$ is increased,

$$\frac{d\theta_N}{d\lambda} = \frac{1}{\Lambda \cdot \cos\theta_{L1}} + \frac{1}{\Lambda \cdot \cos\theta_{L2}} + \ldots\ldots + \frac{1}{\Lambda \cdot \cos\theta_{L\#}} \tag{1}$$

If two gratings are the same, the dispersion is after N diffractions

$$\frac{d\lambda}{d\theta_N} = \frac{N}{\Lambda \cdot \cos\theta} \tag{2}$$

Compared to that of 1-SBC, the equivalent dispersion of N-SBC is increased by *(N-1)* times, and the corresponding spectral bandwidth $\Delta\lambda_T$ is,

$$\Delta\lambda_N = \frac{\Delta\theta \cdot \Lambda \cdot \cos\theta}{N} \tag{3}$$

Therefore, the spectral interval can be compressed to *1/N* that of 1-SBC only by means of a pair of gratings. As a result, the number of the SBC lasers could be increased by *(N-1)* times in the same gain spectral range, and the combining power would be greatly improved.

In this work, two 4.7 µm QCLs were spatially arranged in the SBC direction, each with an emitting aperture width of 8 um, a cavity length of 5 mm, a front facet reflectivity of 16%, a rear facet reflectivity of 95% and a polarization of TM, as provided by Institute of Semiconductors, CAS. The sub-beams emerging from the QCLs were collimated by two aspherical lenses from Lightpath (f = 1.87 mm, NA = 0.85), and spatially combined by two Al-coated mirrors with offset d of 4.5 mm. Along the beam combining direction, a transform lens with f_T of 300 mm was placed to image all the sub-beams onto the grating with the last diffraction. Two 300 lines/mm blazed, gold-coated gratings were employed with the 1st diffraction efficiency of greater than 90% for P-polarized light in the wavelength range from 4.5 µm to 5.0 µm. An antireflection-coated $\lambda/2$ plate was inserted to rotate the TM-polarized laser of QCLs into P polarization with respect to the plane of incidence at the grating. The reflectivity of the output coupler was chosen to be ~30%. The output spectrum was recorded with a fourier transform infrared spectrometer (OSA207C, Thorlabs) and the laser power was measured by using a thermopile detector (10A-V1.1, Ophir).

3. Experimental results and analysis

The CW power and spectrum versus the current characteristics of QCLs under free-running operation at the heatsink temperature of 20 °C are shown in Fig. 2. Two QCLs were driven independently due to the different performance. The threshold current, slope efficiency and the CW power at 1200 mA were 830 mA, 0.90 W/A and 336.8 mW for QCL_1, respectively, and 830 mA, 1.13 W/A and 399.6 mW for QCL_2, respectively. Both free-running spectrum of QCLs were distributed around 4.7 um. Under the same current, the wavelength of QCL_1 was 2 2.5 nm longer than that of QCL_2. At the high current, the spectrum of QCL_1 appears secondary peaks, reducing the intensity of the main peak.

Figure 3 presents the combining spectrum of two QCLs after 1-SBC, 2-SBC and 3-SBC at the current of 1200 mA, respectively. For all three combining spectra, two distinct peaks

Optics EXPRESS

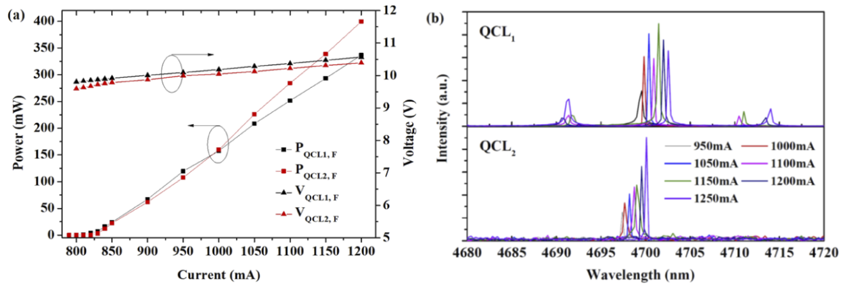

Fig. 2. (a) CW power and (b) spectrum vs. current characteristics of QCLs under free-running operation.

can be observed clearly. As the number of diffractions increased, the spectral interval became smaller. The intervals between the two peaks were $\Delta\lambda_1 = 36.95$ nm for 1-SBC, $\Delta\lambda_2 = 17.16$ nm for 2-SBC, and $\Delta\lambda_3 = 12.22$ nm for 3-SBC. Multiple relationships existed between the three intervals: $\Delta\lambda_2/\Delta\lambda_1 = 1/2.15$, $\Delta\lambda_3/\Delta\lambda_1 = 1/3.02$. The angles of the two gratings deviated from the design value because of the limitation of grating size and position, and to avoid blocking the combining beam, resulting in the shifting of the central wavelength. However, the spectral interval was in good agreement with the predicted one.

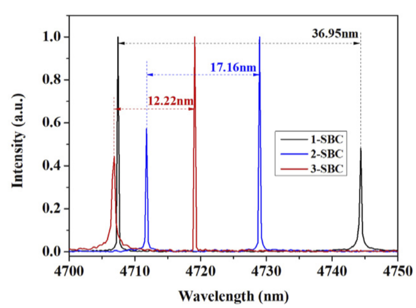

Fig. 3. Combining spectrum after 1-SBC, 2-SBC and 3-SBC at 1200mA.

Figure 4 depicts the CW power and the combining efficiency (η_o). versus the current characteristics of QCLs after 1-SBC, 2-SBC and 3-SBC. The combining efficiency (η_o) is defined as the ratio of the combined power to the free-running power. It can be seen that the CW power and η_o decreased slightly with the increase of diffraction times. For QCL_1, shown in Fig. 4(a), the threshold current, slope efficiency, the maximum CW power and η_o at 1200 mA were 810 mA, 0.50 W/A, 195.1 mW, and 57.9% for 1-SBC; 820 mA, 0.51 W/A, 189.5 mW, and 56.3% for 2-SBC; and 830 mA, 0.49 W/A, 171.0 mW, and 50.8% for 3-SBC, respectively. For QCL_2, shown in Fig. 4(b), the threshold current, slope efficiency, the maximum CW power and η_o at 1200 mA were 810 mA, 0.52 W/A, 195.7 mW, and 50.0% for 1-SBC; 800 mA, 0.51 W/A, 206.8 mW, and 51.7% for 2-SBC; and 830 mA, 0.45 W/A, 167.6 mW, and 50.8% for 3-SBC, respectively. Although the SBC power of QCL_1 and QCL_2 under the same diffraction times was close to each other, η_o of QCL_2 is 6% ~ 8% lower than that of QCL_1, which may be caused by the mismatch of the pointing or polarization of QCL_2, resulting in the failure to achieve good resonance under external feedback.

In order to evaluate the influence on the SBC power with different numbers of diffractions, the power ratio P_N/P_{N-1} is defined as the Nth diffraction power attenuation ratio $\eta_{D,\ N-SBC}$, shown in Fig. 5. To reduce the effect of the power meter background noise, $\eta_{D,\ N-SBC}$ under 1000

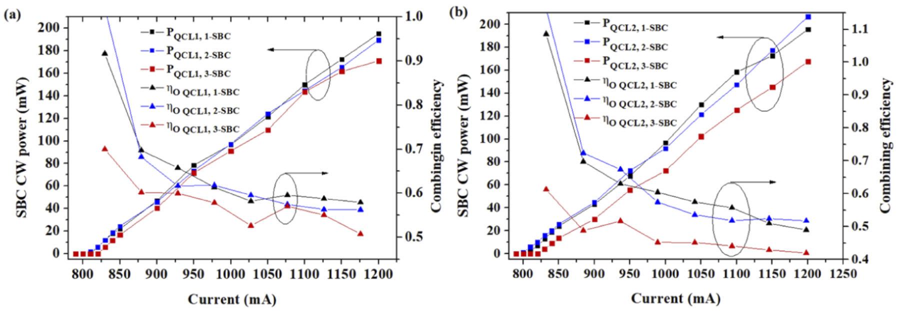

Fig. 4. CW power and combining efficiency (η_o) *vs.* current characteristics of QCL_1 (a) and QCL_2(b) after 1-SBC, 2-SBC and 3-SBC.

mA to 1200 mA were calculated and the average value was taken. For QCL_1, $\eta_{D,\,2-SBC}$ and $\eta_{D,\,2-SBC}$ was 0.99 and 0.94, respectively. For QCL_2, $\eta_{D,\,2-SBC}$ and $\eta_{D,\,2-SBC}$ was 0.98 and 0.82, respectively. As can be seen from the results, $\eta_{D,2-SBC}$ of QCL_1 and QCL_2 was close, and the power attenuation was low. But $\eta_{D,3-SBC}$ appeared to decrease significantly, especially for QCL_2. It was possible that with the increase of diffraction times, the deviation from the component's performance was also superimposed and magnified, resulting in less effective feedback.

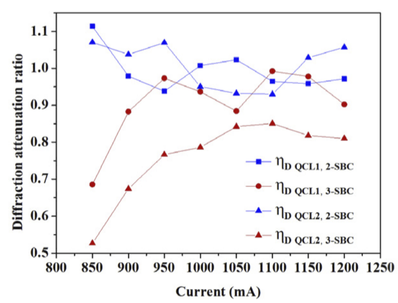

Fig. 5. N-th diffraction power attenuation ratio vs. current.

Figure 6 demonstrates the spot distribution before and after 3-SBC. The two separated spots overlap on the photosensitive card (VRC6H, Thorlabs). No beam quality testing instrument that is suitable for MIR is available. Thus, it is difficult to measure the SBC beam quality at different times of diffraction. However, according to the previously reported results [6], the beam quality of SBC is slightly deteriorated under the effect of grating dispersion, but is still close to that of a single emitter. In subsequent experiments, we plan to purchase relevant equipment for testing.

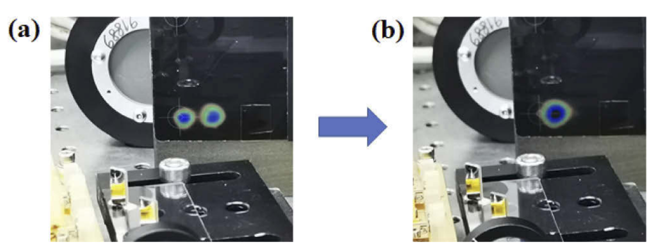

Fig. 6. Spot distribution before and after SBC with three diffractions.

4. Conclusion

A dense SBC method that involves multiplexing a pair of reflective gratings arranged in a V-shaped configuration is proposed. A novel SBC structure in a modified Littman-Metcalf setup with two blazed gratings for wavelength selective optical feedback is built. The SBC spectral bandwidth of QCLs can be compressed several times by increasing the number of diffractions via the round-trip propagation between two gratings. The SBC spectral interval of QCLs is reduced from 36.95 nm to 12.22 nm, and the SBC power can be further improved within a given spectrum range by increasing the number of QCLs, thereby providing an effective technical approach to realize an MIR laser with higher power and high beam quality. At the same time, the physical size of the laser source can be effectively compressed by optical path folding, which is convenient for engineering application.

Funding. National Natural Science Foundation of China (61991433); Pilot project of CAS (XDB43030302); Equipment pre research (2006ZYGG0304); R&D Program of Jilin Province (20190302042GX); Key R & D project of Guangdong Province (2020B090922003).

Acknowledgments. None.

Disclosures. The authors declare that there are no conflicts of interest related to this article.

Data availability. No data were generated or analyzed in the presented research.

References

1. J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, "Quantum Cascade Laser," Science **264**(5158), 553–556 (1994).
2. M. Razeghi, W. Zhou, S. Slivken, Q. Y. Lu, D. Wu, and R. McClintock, "Recent progress of quantum cascade laser research from 3 to 12 µm at the Center for Quantum Devices," Appl. Opt. **56**(31), H30–H44 (2017).
3. P. Figueiredo, M. Suttinger, R. Go, E. Tsvid, C. Kumar, N. Patel, and A. Lyakh, "Progress in high-power continuous-wave quantum cascade lasers," Appl. Opt. **56**(31), H15–H23 (2017).
4. Y. Bai, N. Bandyopadhyay, S. Tsao, S. Slivken, and M. Razeghi, "Room temperature quantum cascade lasers with 27% wall plug efficiency," Appl. Phys. Lett. **98**(18), 181102 (2011).
5. C. C. Cook and T. Y. Fan, "Spectral Beam Combining of Yb-doped Fiber Lasers in an External Cavity," in *Advanced Solid State Lasers*, M. Fejer, H. Injeyan, and U. Keller, eds., Vol. 26 of OSA Trends in Optics and Photonics (Optical Society of America, 1999), paper PD5.
6. S. Hugger, R. Aidam, W. Bronner, F. Fuchs, R. Lösch, Q. K. Yang, J. Wagner, E. Romasew, M. Raab, H. D. Tholl, B. Höfer, and A. L. Matthes, "Power scaling of quantum cascade lasers via multi-emitter beam combining," Opt. Eng. **49**(11), 111111 (2010).
7. A. K. Goyal, M. Spencer, O. Shatrovoy, B. G. Lee, L. Diehl, C. Pfluegl, A. Sanchez, and F. Capasso, "Dispersion-compensated wavelength beam combining of quantum-cascade-laser arrays," Opt. Express **19**(27), 26725–26732 (2011).
8. A. Goyal, T. Myers, C. A. Wang, M. Kelly, B. Tyrrell, B. Gokden, A. Sanchez, G. Turner, and F. Capasso, "Active hyperspectral imaging using a quantum cascade laser (QCL) array and digital-pixel focal plane array (DFPA) camera," Opt. Express **22**(12), 14392–14401 (2014).
9. V. Daneu, A. Sanchez, T. Y. Fan, H. K. Choi, G. W. Turner, and C. C. Cook, "Spectral beam combining of a broad-stripe diode laser array in an external cavity," Opt. Lett. **25**(6), 405–407 (2000).
10. M. G. Littman and H. J. Metcalf, "Spectrally narrow pulsed dye laser without beam expander," Appl. Opt. **17**(14), 2224–2227 (1978).
11. Z. H. Gu, J. C. Zhang, S. Q. Zhai, N. Zhuo, S. M. Liu, J. Q. Liu, L. J. Wang, F. Q. Liu, and Z. G. Wang, "Spectral beam combining of discrete quantum cascade lasers," Opt. Quantum Electron. **53**(10), 584 (2021).