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# External-cavity beam combining of 4-channel quantum cascade lasers

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## HIGHLIGHTS

- We demonstrate a new structure of beam combining of quantum cascade lasers with an external cavity.
- A grating and an output coupler are aligned to realize an external-cavity system.
- The system do not have heat crosstalk so that the system can be used for high power beam combining of QCLs.
- A beam combining efficiency of 35% (up to 75% near threshold) is obtained with a beam quality $M^2$ of 5.5.
- The differences of spot characteristic between coupled and uncoupled are also showed in this letter.

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## ABSTRACT

We demonstrate an external-cavity (EC) beam combining of 4-channel quantum cascade lasers (QCLs) with an output coupler which makes different QCL beams propagating coaxially. A beam combining efficiency of 35% (up to 75% near threshold) is obtained with a beam quality $M^2$ of 5.5. A peak power of 0.64 W is achieved at a wavelength of 4.7 μm. The differences of spot characteristic between coupled and uncoupled are also showed in this letter. The QCLs in this EC system do not have heat crosstalk so that the system can be used for high power beam combining of QCLs.



## 1. Introduction

Quantum cascade lasers (QCLs), since it was first reported in 1994 [1], have been widely employed in many areas such as free space optical communication, gas sensing and directed infrared countermeasure (DIRCM) [2–4]. After more than 20 years development, high power up to 5.1 W has been obtained in continuous-wave mode at room temperature from a single emitter and the lasing wavelength has covered the mid, far-infrared and terahertz spectrum range [5,6]. Nevertheless, the output power of single emitter device is not enough for DIRCM system. Beam combining of QCLs can serve more output power and well good beam quality. In the past years, beam combining of QCLs including both coherent and incoherent methods have been comprehensively researched.

Coherent beam combining of QCLs has been mainly demonstrated in two different systems: Michelson cavity and Dammann grating [7,8], which may lead to a high combining efficiency and a good beam quality. However, that always need a complicated structure or grating (Dammann grating was fabricated with complicated processes) and difficult adjustment, along with physical effects like the phase mismatch, power modulation caused by the injection current and so on. Incoherent beam combining of QCLs has also been widely done in different ways, such as wavelength beam combining of array with a grating [9], hollow waveguide beam combining (HWBC) [10] wavelength beam combining with an external-cavity (EC) system [11], and spatial beam combining [12]. EC wavelength beam combining is advantageous, because this technique produces a set of closely spaced parallel output beams, strongly overlapping in the far-field, without introducing any coupling losses. And the resulting beam quality ($M^2$ for both fast and slow axes) is close to the single emitter. However, they suffer from a strong heat accumulation, especially for low conversion

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efficiency laser, which will limit the output power. On the other hand, the coaxial spread for spatial beam combining is difficult to obtain by pure optical modulation. So depended on spatial beam combining only, the coaxial problem is hard to solve although this technique possesses very high beam combining efficiency.

In this letter, we take the advantage of EC wavelength beam combining and spatial beam combining for avoiding their heat accumulation and solving uncoaxially propagation. We demonstrate a new QCL beam combining system, which was assembled with four single emitters and a closed-loop wavelength beam combing system. 4-channel QCLs emitting at $\lambda \sim 4.7$ μm propagating coaxially were obtained with a peak optical power of 0.64 W and a combining efficiency of 35%. A beam quality factor $M^2$ around 5.5 is achieved in both directions using this scheme. The QCLs in this system do not have heat crosstalk so that the system can be used for high power beam combining of QCLs. Moreover, the system can also be used for multiple wavelength beams combining by adjusting the incident angle of QCL beam to blazed grating.

## 2. External-cavity beam combing setup

The QCL wafer was grown on an n-doped InP substrate wafer by solid-source molecular beam epitaxy (MBE) and the active core structure is identical to Ref. [13]. After growth, the ridge was processed by conventional photolithography and a nonselective wet chemical etching. InP cladding was epitaxied as upper waveguide and $SiO_2$ served as an electrical insulation around the laser ridges and was deposited. Then Ti/Au layer was deposited as top contacts, followed by an Au layer electroplated to better conduct the current and heat on the laser surface. After the wafer was thinned down to 120 μm, the Ge/Au/Ni/Au metal contacts were formed as substrate layer. The lasers were mounted epilayer side down onto SiC heat sinks and wire bonded. Finally, high reflectivity (HR) coating $Al_2O_3$/Ti/Au/$Al_2O_3$ was deposited on the rear facet.

The experimental setup is presented in Fig. 1. Four single emitters were installed in the copper ladder heat sink. Because of their divergence angles of $\sim 40° \times 30°$ ($1/e^2$ far-field half-angle for the fast and slow axis), the QCLs are individually collimated with anti-reflectivity (AR) coated high-aperture collimation lenses (CL) from LightPath (NA = 0.86, f = 1.88 mm). The collimated beams are reflected by Au coated mirrors to overlap beams closed to each other. Then a $\lambda/2$ plate is installed to increase diffraction efficiency before the light incidence to the blazed grating (Gold coated, 240 lines/cm, blazed wavelength is 4.6 μm). The grating period is chosen so that the grating has only zero- and first-order diffraction orders to eliminate efficiency losses of higher diffraction orders.

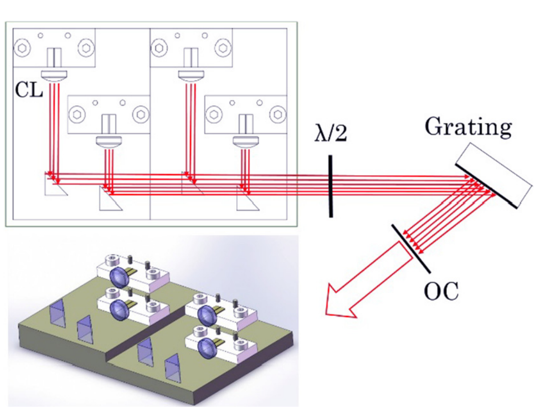


**Fig. 1.** The scheme of EC beam combining of QCLs. Both 2D and 3D sketch maps are showed.

The EC extends between the rear facet of the four QCLs and the output coupler (OC). The OC is a Ge plate presenting around 40% of Fresnel reflection. Codirectional propagation of the individual beams is forced by the flat Ge OC, because the directions of propagation of the output beams are all normal to this OC.

## 3. Output characteristic of the system

The power-current-voltage (PIV) characteristic of four QCLs (marked as QCL1, QCL2, QCL3, QCL4) for EC beam combining is showed in the Fig. 2(a), the output power was measured with a calibrated thermopile detector placed directly in front of the uncoated laser facet at a condition of 50 kHz repetition frequency and 1 μs pulse width. The output peak power of QCL1, 2, 3, 4 is 0.44, 0.39, 0.57, 0.43 W respectively at a current of 700 mA. Fig. 2(b) shows the total power before and after EC beam combining as a function of injection current. The total power of four QCLs is 1.83 W before EC beam combining and 0.64 W after EC beam combining. The inset displays the efficiency of beam combining at different injection current. A high efficiency of 72% is obtained at 320 mA and remains around 35% when the injection current increase to 700 mA. The high efficiency around the threshold is caused by that the reflectivity of Ge OC is higher than the uncoated QCLs front facet, which leads to the decrease of the threshold current. The real efficiency around 35% can be explained by the fact that the reflectivity of front facets of QCLs is about 27% and the finite efficiency of the grating has to be passed twice in one round-trip. The beam combining efficiency can be enormously improved by depositing the AR coating on the front cavity facet. In theory, the beam combining efficiency should be higher than that of pure EC wavelength

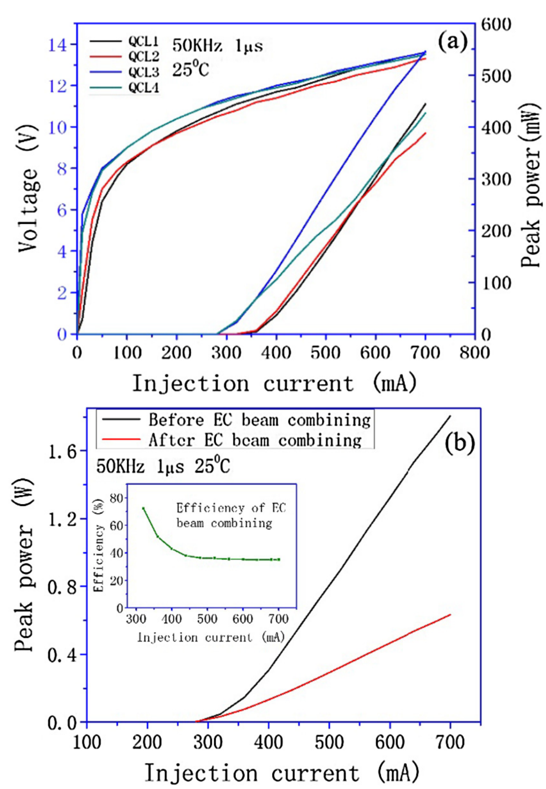


**Fig. 2.** (a) Four different QCLs peak power versus the injection current of in pulse mode at a condition of 5% duty circle and 1 μs pulse width along with the V-I curves at 25 °C. (b) Optical peak power as a function of current for the total power and the beam-combined output power. The inset shows the beam combining efficiency changes with the injection current.