



# Passive coherent beam combining of quantum-cascade lasers with a Dammann grating

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## ABSTRACT

An external cavity with a binary phase grating has been developed to achieve the coherent beam addition of five quantum-cascade lasers emitting at 4.65  $\mu\text{m}$ . The combining of these five emitters is achieved by a binary phase grating or Dammann grating able to separate an incident beam into five beams of equal intensities with a 75% efficiency. A CW output power of  $\sim 0.65$  W corresponding to a combining efficiency of 70% with a good beam quality is obtained. More results concerning output power, combining, efficiency stability and beam quality and spectrum are exposed.

**Keywords:** Quantum cascade lasers, beam combining, binary phase grating, mid-infrared, optical countermeasures.

## 1. INTRODUCTION

There is an increasing need for powerful sources in the mid-infrared with a good beam quality for DIRCM applications. The quantum cascade laser (QCL)<sup>1</sup> is a promising solution for optical countermeasures since powerful emission in the mid-infrared has recently been obtained from QCL. An output power of 5.1 W was reported in continuous regime (CW) at room temperature (RT) from a single narrow-waveguide emitter<sup>2</sup>. But the maximum power achievable under continuous regime (CW) operation at room temperature is now limited by the heating of the active region. In order to circumvent this limitation, an external beam combining technique can advantageously be applied to deliver the power of several QCL while keeping the beam quality of a single emitter. The most direct method to achieve the beam addition of QCL is the polarization combining<sup>4</sup> or the spectral beam combining<sup>5</sup>. In this study, the passive coherent beam combining (CBC) of several QCL in external cavity is explored.

A Michelson external cavity has recently been developed to achieve the CBC of two QCL with a combining efficiency of 85% and a good beam quality<sup>6</sup>. To combine more emitters an external cavity with a N to 1 beam combiner is designed. The coherent beam addition of 10 GaAlAs laser diodes has already been demonstrated with a combining efficiency of 68% and a far-field profile of the combined beam identical to the one of a single emitter<sup>7</sup>. The same method is applied here to demonstrate the coherent beam addition of five QCL in CW regime.

## 2. EXPERIMENTAL SETUP

The QCL used are made of strain balanced  $\text{Ga}_{0.30}\text{In}_{0.7}\text{As}/\text{Al}_{0.7}\text{In}_{0.30}\text{As}$  active regions on an InP substrate. The ridge was ICP (Inductively Coupled Plasma) etched and buried into iron doped InP by MOCVD regrowth. Electrodeposition of gold was performed for a better heat extraction. Further thermal improvement is obtained via epi-down mounting on AlN submount with gold tin soldering. With a highly-reflective (HR) coating on the rear facet and no coating on the output facet, 5 mm long lasers exhibit 600 mW output power in CW operation at 4.65  $\mu\text{m}$  with a spectral bandwidth of  $\sim 100$  nm and 1.3  $\text{kA}\cdot\text{cm}^{-2}$  threshold current density. In order to prevent laser oscillation of the emitters alone in CW operation and thus to facilitate their phase locking in the external cavity, the QCL output facets were antireflection (AR) coated (the rear facet being HR coated). The coating is made of two layers of  $\text{SiO}_2$  and  $\text{TiO}_2$  and is estimated to  $R < 2\%$  at a wavelength of 4.65  $\mu\text{m}$ .

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The experimental setup is presented in Figure 1. The external cavity extends between the rear facet of the five QCL and the output coupler (OC). The OC is a GaAs plate presenting around 30% of Fresnel reflection with its rear facet being AR coated ( $R \sim 2\%$ ). Because of their high divergence angle the QCL are collimated individually with AR coated high aperture collimation lenses (CL) from LightPath ( $NA = 0.86$ ,  $f = 1.88$  mm). Because of their intersubband lasing transition, the output emission of QCL is linearly polarized along the normal direction to the layers of the active region. This well-defined polarization will ensure that the polarization states of the five emitters are parallel which is essential for coherent coupling.

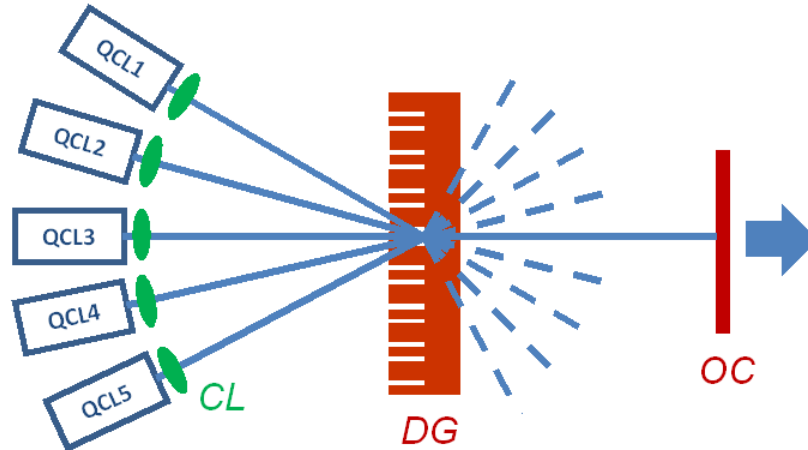


Figure 1. Experimental setup. QCL: HR-AR QCL, CL: collimation lens, DG: Dammann grating, OC: output coupler.

The coherent combining process in such interferometric resonators can be easily explained. Since a laser tends to oscillate on the mode with the lowest threshold, the common cavity scheme will ensure phase locking between the different lasers and will select the right longitudinal mode so that there are constructive interferences at the common output end (corresponding to the 0<sup>th</sup> order of the Dammann grating (DG)) and destructive interferences on the other orders of the grating (some of them are represented by dashed lines in Figure 1). If these conditions are fulfilled, the combining efficiency of the cavity is equal to the splitting efficiency of the DG<sup>8</sup>. This self-organization process is totally passive since it is based on loss minimization in the external cavity.

### 3. THE DAMMANN GRATING

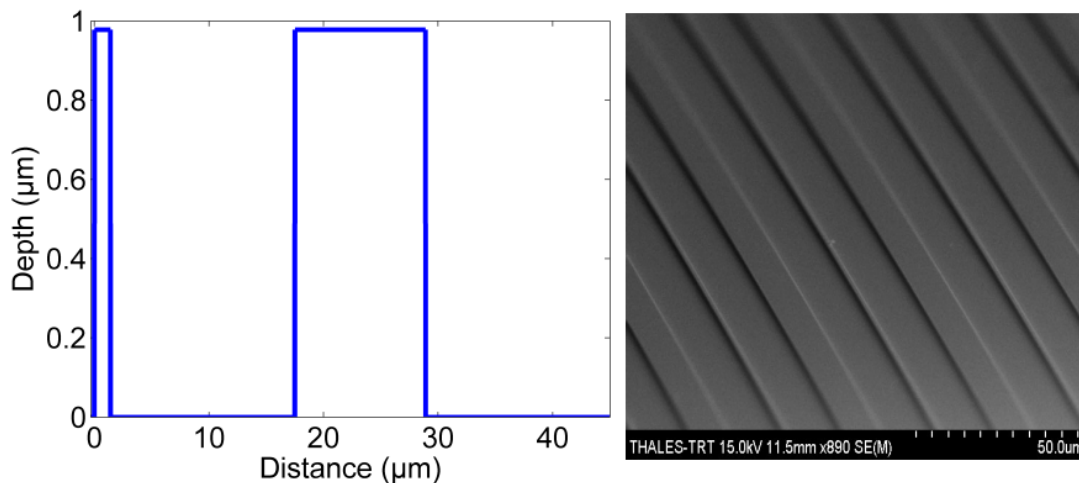


Figure 2. (Left) Profile of one DG period (Right) SEM view of the DG before AR coating.

The coupling between the five emitters is achieved by a binary phase grating or Dammann grating<sup>9</sup>. Multilevel phase gratings or continuous phase gratings present a higher efficiency but are more difficult to fabricate. The binary phase profile (see Figure 2) is optimized so that the grating can separate an incident beam at  $4.65 \mu\text{m}$  into five beams of equal intensities with a good splitting efficiency (defined as the ratio of the power in the 5 central orders to the total power). The optimized profile is fabricated in GaAs with

UV optical lithography and ICP (Inductively Coupled Plasma) etching. The grating is then AR coated on both the etched facet and the rear one. The coating ( $\text{SiO}_2$  and  $\text{TiO}_2$ ) is the same as the one used for the QCL. An experimental splitting efficiency of  $\sim 75\%$  is obtained along with a good uniformity between the five central orders intensities (see Figure 3). These results are in good agreement with theoretical calculation.

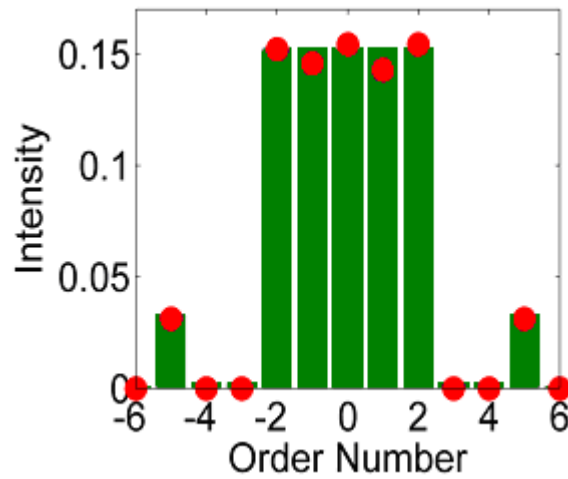


Figure 3. Calculated (Green) and measured (Red) orders intensities of the fabricated DG with its AR coating.

## 4. EXPERIMENTAL RESULTS

### 4.1 Output power

The five QCL are studied in their own separate external cavities (with external lengths corresponding to those used in the 5-arms cavity). The characteristics of the QCL in their external cavities are summarized in Table 1. Because of their different waveguide sizes, the output powers versus current curves obtained from these QCL in external cavity were quite different (see Figure 4).

Table 1: QCL characteristics in external cavity

QCL	1	2	3	4	5
Waveguide size ( $\mu\text{m}$ )	6	6	8	8	8
Length (mm)	4	4	4	5	5

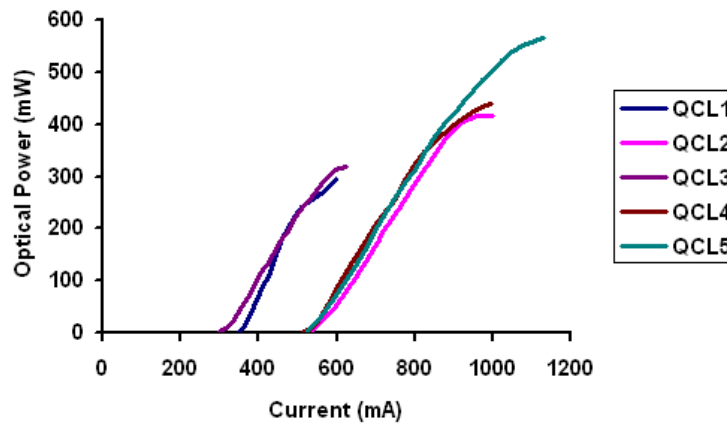


Figure 4. QCL power versus current characteristics

Consequently, in order to make the intensities of the five arms be equal, the currents of the five QCL are set so that the output powers they had in their own external cavities were equal. The sum of the powers obtained from these five external cavities is represented on

Figure 5 (blue curve). The current values on the X axis are those of the QCL placed on the 0<sup>th</sup> order of the DG, the currents of the other QCL being different but leading to the same output power in their own separate external cavities as explained before.

By introducing a 25/75 beamsplitter in the external arm (between the QCL and the OC) we could add controlled losses for each QCL in external cavity. Thus, additional simple pass losses of 25% were introduced in each cavity to simulate the losses of the DG. The sum of the output powers obtained from the five QCL in external cavity with 25% additional losses are represented on Figure 5 (green curve). Again, the current values on the X axis are those of the QCL placed on the 0<sup>th</sup> order of the DG, the currents of the other QCL being different but leading to the same output power in their own separate external cavities with the 25% additional losses.

Two different geometrical configurations of the 5-arm cavity are studied and compared here. The first one is similar to the one presented in Figure 1 with the 5 arms of nearly equal lengths (~ 26, 28, 30, 32 and 34 cm), while the second one is identical but has its central arm 10 cm longer (~ 26, 28, 40, 32 and 34 cm).

The output power of the complete cavity (as represented in Figure 1) is measured at different sets of currents, corresponding to equal intensities in the five arms as described before (see Figure 5). For the first configuration (“short” central arm), an output power of 0.5 W was obtained in CW regime. The output power is quite stable (relative fluctuation  $< \pm 10\%$  peak-to-peak at maximal power), at least over one hour of free running in non protected environment and no specific precaution (except QCL thermal stabilization). These power fluctuations were not observed when studying the CBC of two QCL<sup>9</sup>. The increase of the output power fluctuations with the number of sources combined has already been described<sup>10</sup>. For the second configuration (“long” central arm), an output power of 0.65 W was obtained in CW regime with a relative fluctuation  $< \pm 5\%$  peak-to-peak.

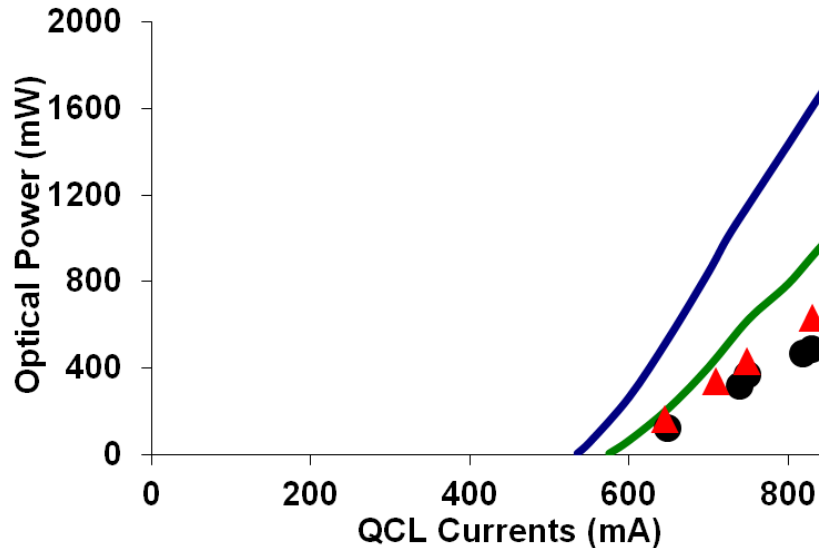


Figure 5. Output power versus input current: circles, output “short” cavity; triangles, output “long” cavity; blue solid curve, sum of the five individual QCL; green solid curve, sum of the five individual QCL with 25% additional losses.

## 4.2 Combining Efficiency

The global cavity presents an output power reduced compared to the sum of the powers of the QCL in their external cavities since only ~ 40% of the available power is effectively obtained in the “long” cavity case (see the blue curve in Figure 5). A big part of this lost output power is due to the additional losses introduced by the DG (see the green curve in Figure 5). Nevertheless, there is a non negligible part of the available output power still missing, even if the additional losses of the DG are taken into account. This is due to the fact the DG does not work at its maximal combining efficiency. The combining efficiency of the DG is defined as the power transmitted in the 0<sup>th</sup> order (between the DG and the OC) divided by the sum of the powers in all the transmitted orders (the 0<sup>th</sup> order plus all the existing orders between the DG and the OC represented by dashed lines in Figure 1). In Figure 6, we show the calculated orders intensities of a DG illuminated by five beams with the proper relative phases along with the measured ones. A combining efficiency of ~ 66% is measured for the “short” configuration and ~ 70% is measured for the “long” configuration at maximal power (to be compared to the theoretical maximal combining efficiency of 75%). The difference between the DG combining efficiency (75%) and the measured ones on the one hand and the differences between the measured combining efficiencies in the “short” and “long” cavity configurations (66% and 70%) on the other hand, can be explained by an imperfect phase locking between the five arms. As explained before, passive CBC is only based on longitudinal mode selection in the N-arms resonator. If no common longitudinal mode exists within the spectral gain bandwidth of the

QCL, the system still selects the mode with the least losses. In this case, because of residual phase mismatch between the  $N$  arms, a part of the available power will be diffracted into the lossy orders of the DG (the dashed lines in Figure 1), resulting in a reduced combining efficiency and thus a reduced output power<sup>10</sup>. To quantify the combining efficiency that can be obtained from such  $N$ -arm cavities for different geometrical configurations and for a gain bandwidth of  $100 \text{ cm}^{-1}$ , we used the effective reflectivity model in a non-stable environment described in<sup>10</sup>. To model the perturbations caused by the non-protected environment, we introduced a random length deviation of  $\lambda = 4.6 \text{ }\mu\text{m}$  on the different arm lengths (see<sup>10</sup>). We estimate a combining efficiency of  $\eta = \eta_{\text{max}} \cdot 88\% = 66\%$  in the “short” cavity case and  $\eta = \eta_{\text{max}} \cdot 93\% = 69\%$  in the “long” cavity case. Influences of the arm length difference and the number of arms on the performance of the external cavity are quite in good agreement with the theoretical predictions.

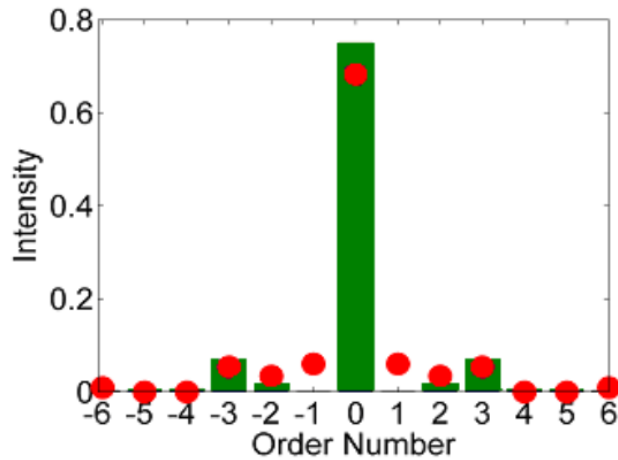


Figure 6. Green: calculated orders intensities of a DG lit by five beams with the proper relative phases; Red: Measured orders intensities.

### 4.3 Beam quality

Beam quality measurements on the output beam were performed to verify that the external cavity has effectively improved the brightness of a single QCL. These measurements were performed with a  $20\mu\text{m}$  slit and a HgCdTe detector (see Figure 7). The combined beam was still nearly diffraction-limited since the  $M^2$  parameter (second-order moments definition) was measured to be  $M^2_x < 1.2$  and  $M^2_y < 1.6$  and was very close to the  $M^2$  value measured from the individual QCL in external cavity ( $M^2_x = 1.2$  and  $M^2_y = 1.5$ ).

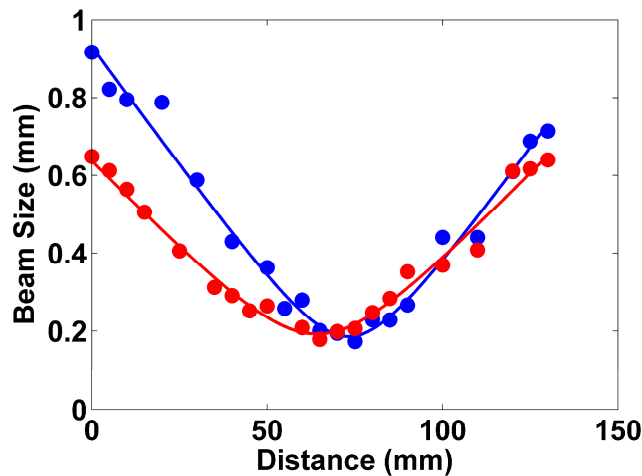


Figure 7. Signal beam quality measurements (fast-axis experiment, blue dots; slow-axis experiment, red dots; solid curves, fit).

## 5. CONCLUSION

The coherent beam addition of five quantum cascade lasers in an external cavity using a binary phase grating was demonstrated. A power of 0.65 W in continuous regime at room temperature corresponding to a combining efficiency of 70% were obtained. The far-field profile of the combined beam is found to be identical to the one of a single emitter ( $M^2 < 1.6$ ). The method presented here is shown to be an efficient way to increase the brightness of QCLs and thus to address the power scaling issue of these components. More power should be obtained from this cavity using a more efficient beamsplitter such as multilevel phase gratings or continuous phase gratings.

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