Invited Paper

Beam steering in quantum cascade lasers with optical feedback

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ABSTRACT

Quantum cascade lasers are semiconductor lasers based on intersubband transitions that have developed rapidly and become the most suitable mid-infrared laser sources, due to their compactness, efficiency and high room temperature performances. High-power mid-infrared quantum cascade lasers are performant sources for optical countermeasures, including night vision blinding and missile out steering. However, some drawbacks arise with high power lasers that usually lead to a strong degradation of the beam quality. For instance, beam steering is known to be one of the limiting factors inducing an irregular distribution of the optical power within the near-field beam profile. This phenomenon has already been observed in high power quantum cascade lasers before and can be explained by four-wave mixing interaction among the existing transverse modes. It dramatically degrades the far-field of the laser emission, and prevents its use for applications where high beam quality is required. In this work, we show for the first time that the use of a small amount of optical feedback reinjected into a high power quantum cascade laser emitting at 4.6 μm and with poor beam quality allows a total suppression of the beam steering effect without sacrificing the near-field profile.

Keywords: Quantum cascade laser, optical feedback, beam steering

1. INTRODUCTION

Based on radiative transitions between two subbands of the conduction band, quantum cascade lasers (QCLs) can emit over a wide range of wavelengths from about 3 μm up to 250 μm, depending on their quantum design.[1] Mid-infrared QCLs have become over the past few years privileged sources for many applications, due to their small size, stability and good performances at room temperature.

Some specific applications, such as high-precision spectroscopy, selective surgery or optical countermeasures, require very high output powers in the mid-infrared range. A straightforward idea is to increase the width of the QCL active region, in order to increase the volume of the gain region. QCLs as broad as 400 μm have been demonstrated, resulting in peak powers as high as 203 W.[2] However, these wide active regions also result in inefficient heat-load dissipation and strong deterioration of the beam profile. A broader cavity will indeed support numerous transverse modes, leading to degraded far-fields.

The main phenomena degrading the beam quality is the beam steering effect. It originates from the large third-order susceptibility in QCLs, which leads to a nonlinear coupling between the transverse modes and hence to four-wave mixing interaction and phase coherence.[3] The electric field in the cavity can be expressed as a combination of the fields of all the transverse modes, resulting in a deteriorated far-field.[4] This beam steering effect appears as soon as more than one transverse mode co-exist in the cavity, i.e. for active regions typically broader than 12 μm for a QCL emitting around 5 μm.

In interband lasers, it has been shown that applying optical feedback can significantly improve the beam quality of broad-area lasers.[5,6] This technique consists in reinjecting part of the light emitted by the laser back

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into the cavity after reflection on a mirror, which will modify the static and dynamical properties of the device. Depending on the two feedback parameters, the external cavity length and the feedback ratio, defined as the ratio between reinjected and emitted powers, optical feedback can either excite or suppress the higher-order cavity modes.[7,8]

It has been demonstrated that in narrow-ridge QCLs, optical feedback has a similar impact than on interband lasers, resulting in threshold reduction, power increase, single- or multimode operation or even chaotic operation.[9,10] In this work, we show that applying optical feedback on a 14 μm-wide QCL emitting around 4.6 μm leads to a complete suppression of the beam steering effect.

2. LASER PERFORMANCES

The QCLs under study are Fabry-Perot QCLs emitting around 4.6 μm. They are adapted from a strain-compensated design[11] and consist of 30 periods of GaInAs/AlInAs grown between two InP cladding layers. The active region is processed using double-trench technology, and a high-reflective coating is added on the back facet. The QCLs are 14 μm wide and 3 mm long. As shown in Figure 1, they can emit up to 78 mW mean power at room temperature, with a duty cycle of 3%, corresponding to 600 ns-long pulses at a repetition rate of 50 kHz. The threshold current is 396 mA at 20°C.

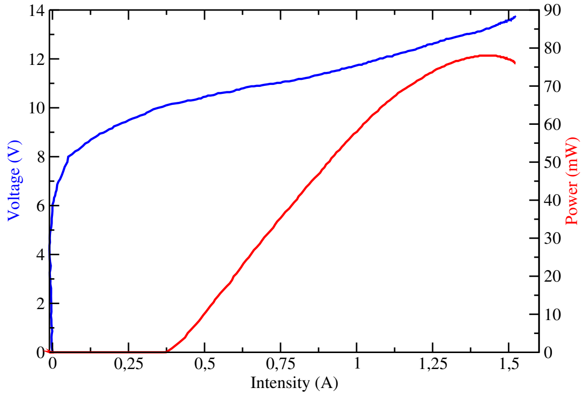

Figure 1. Light-current-voltage characteristics of the QCL under study, for 600 ns-long pulses at a repetition rate of 50kHz.

Layer name	**Refractive index**
Lower cladding layer	3.10
Active region	3.20
First upper cladding layer	3.10
Second upper cladding layer	2.46
Third upper cladding layer	2.21
Dielectric insulation	1.49

Table 1. Material refractive indices used for the simulations.

The modes are simulated by solving the Maxwell's equations with a 2D finite-element method software. The refractive indices of each layer as used for the simulation are indicated in Table 1. The refractive index of the SiO_2 dielectric insulation layer has been measured by Mueller ellipsometry.[12] According to the simulation, two transverse modes can coexist in the laser cavity, as shown in Figure 2 where the TM0 and TM1 modes are represented in a) and b), respectively.

The corresponding effective refractive indices are very close from one another, 3.1297 and 3.1177 respectively, resulting in a beating between these two modes. This leads to the appearance of beam steering in the laser,

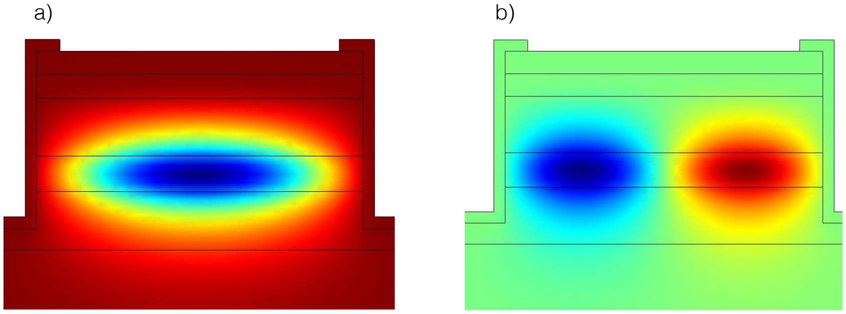

Figure 2. Simulation of the two transverse modes that can exist in the cavity.

and to the deterioration of the beam profile. Indeed, as represented on Figure 3, the horizontal far-field of the studied QCL exhibits two secondary lobes around a central lobe at high bias voltage (12.8 V). From fitting the central lobe of the horizontal far-field by a gaussian profile, its FWHM is 21.2°.

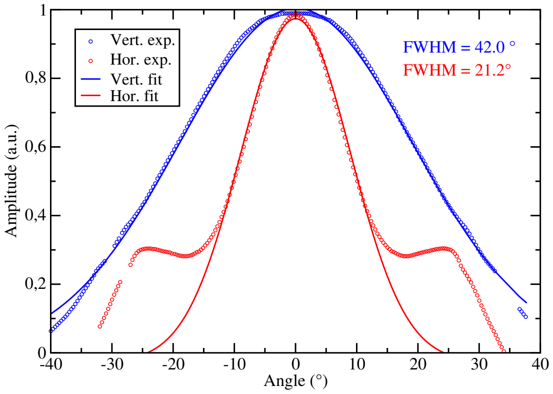

Figure 3. Far-field of the QCL under study, measured horizontally and vertically at 12.8 V.

The broad vertical far-field is typical of QCLs beam profile, it is single-lobe and its FWHM is 42°.

3. OPTICAL FEEDBACK EXPERIMENT

The QCL is inserted into the experimental setup described in Figure 4. The light emitted by the laser is focused on an infrared camera comporting 124×124 pixels using a lens with very short focal length (f = 1.87 mm). The light is split in two paths using a 60/40 beam splitter. On one path, the near field is imaged with the camera, and on the other path, the beam is reflected on a mirror and reinjected into the laser cavity. The feedback ratio is estimated around 5%, corresponding to threshold fluctuations of about 1%. The external cavity length is 22 cm, also equal to the distance between the laser facet and the camera. This means that the laser beam is focused on the feedback mirror and what is reinjected into the QCL cavity is an image of its near-field.

In broad-area lasers, the spatial dependency of the carrier densities and electric field is no longer negligible, a diffusion term for the carrier density and a diffraction term for the photon density appear in the rate equations.[13] Therefore, the relative position Δx of the reinjected beam compared to the emitted beam becomes an important feedback parameter. In order to study the influence of this shift in position, the feedback mirror is mounted on a rotation stage to control the angle θ of the reinjected beam, with a precision of ± 2'.

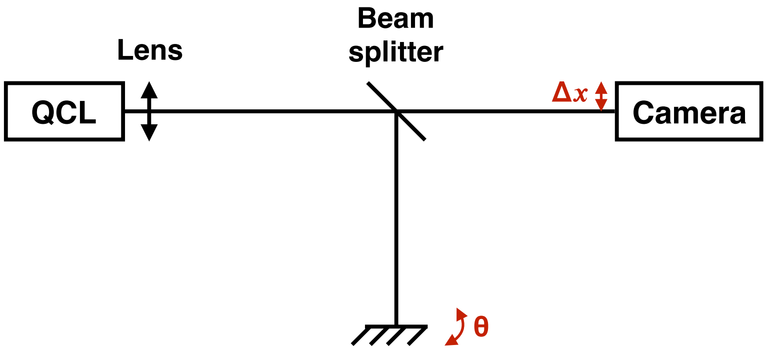

Figure 4. Schematic of the external optical feedback experimental setup.

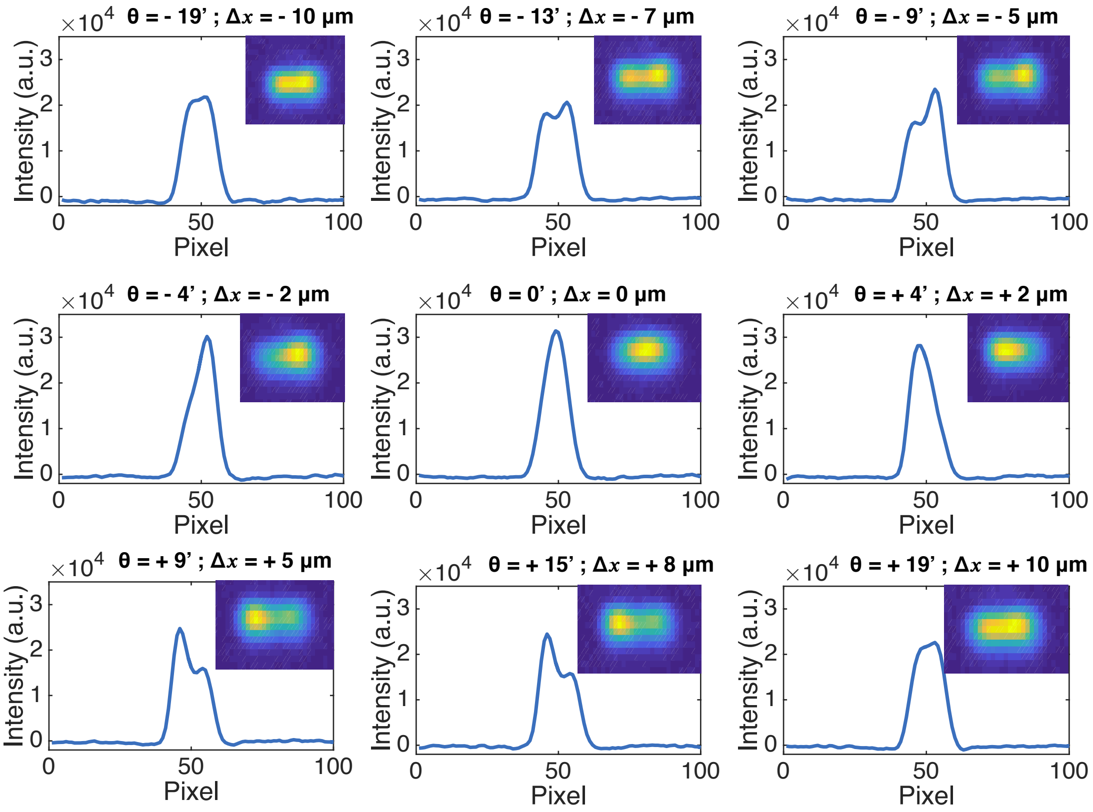

Figure 5. Near-field profiles of the QCL under study under optical feedback, for several feedback angles. The insets present the near-fields as recorded on the camera.

4. BEAM STEERING SUPPRESSION

The near-field profiles of the QCL under study operated at 10.53 V and subjected to optical feedback are presented in Figure 5. For each angle of the feedback mirror, the profile is calculated by summing the intensity of each pixel column, for an original near-field as measured on the camera represented in inset of each graph. The central curve ($\theta = 0'$) correspond to the central position of optical feedback, for which the emitted and reinjected beams are superimposed on the laser facet. The first and last curves ($\theta = -19'$ and $\theta = +19'$) correspond to the case without optical feedback, for which the beam is reinjected outside the laser cavity. In that case, the near-field profile clearly shows the occurrence of beam steering effect: the profile is not homogeneous and presents two maxima.

When varying the angle of the feedback mirror, the two maxima become well-separated ($\theta = -13'$, $\theta = -9'$, $\theta = +9'$ and $\theta = +15'$). One of them is predominant depending on the sign of the angle compared to the central position. Closer to centered feedback ($\theta = -4'$ and $\theta = +4'$), the profile is single-lobe but deviated from the optical axis. Finally, for centered optical feedback, the resulting near-field profile becomes gaussian, and the beam steering is totally suppressed.

This beam steering suppression is still observed close to the maximum power, as shown on Figure 6 at 11.92 V, where the laser emits at 80% of its maximum power.

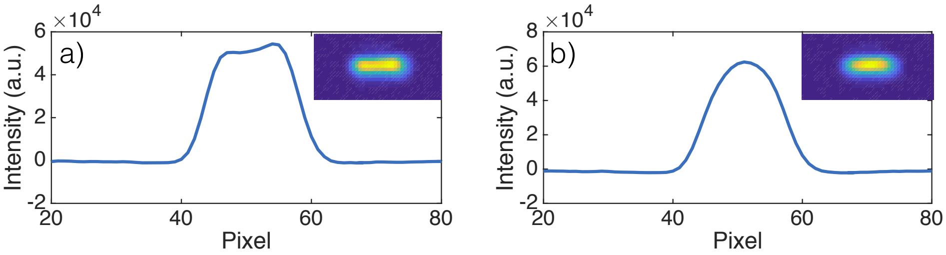

Figure 6. Near-field profiles of the QCL under study at high voltage (11.92 V) without feedback (a) and under centered optical feedback (b).

5. CONCLUSION

Applying centered optical feedback can therefore be used to control the beam quality of high power QCLs by suppressing the beam steering effect and favoring the operation on the fundamental mode TM0. This technique to suppress the beam steering has been validated at several bias currents, including very close to the maximum power. Off-axis emission obtained with out-centered optical feedback could furthermore be exploited for beam deviation without rotating the laser.

Future work will focus on QCLs with wider active regions, in order to conclude whether optical feedback can suppress the beam steering effect in these structures as well, to obtain high power and high beam quality for the applications.

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