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Estimating optical feedback from a chalcogenide fiber in mid-infrared quantum cascade lasers

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The amount of optical feedback originating from a chalcogenide fiber used to couple light from a mid-infrared quantum cascade laser is evaluated experimentally. Threshold reduction measurements on the fibered laser, combined with an analytical study of a rate equations model of the laser under optical feedback, allow estimating the feedback strength between 11% and 15% depending on the fiber cleavage quality. While this remains below the frontier of the chaotic regime, it is sufficient to deeply modify the optical spectrum of a quantum cascade laser. Hence for applications such as gas spectroscopy, where the shape of the optical spectrum is of prime importance, the use of mid-infrared optical isolators may be necessary for fibered quantum cascade lasers to be fully exploited. *© 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [http://dx.doi.org/10.1063/1.4964494]

Quantum cascade lasers (QCLs) are semiconductor lasers based on intersubband transitions within the conduction band,[1] thus covering a wide range of wavelengths from the mid-infrared (IR) up to the terahertz domain. Over the past twenty years, mid-IR QCL technology improved significantly and they now offer over 100 mW in continuous-wave (CW) or pulsed operation at room temperature with thermoelectric cooling. These structures have therefore become privileged sources for applications such as optical countermeasures, free-space communications or gas spectroscopy.[2] For the latter, it can be useful to install the laser system far from the medium under test, and guide the emitted light using an optical fiber. However, conventional silica fibers do not guide mid-IR wavelengths, and new glasses had to be developed.[3,4]

Parasitic optical feedback induced by a reflection on a fiber extremity or by Rayleigh backscattering along the fiber is a well-known phenomenon in the near-IR. Depending on the external cavity length L_{ext} and on the feedback ratio f_{ext}, defined as the percentage of emitted power that is reflected to the laser, optical feedback can either improve or deteriorate laser properties.[5] To avoid any detrimental effect on laser linewidth and operation in near-IR fibered communication systems, fiber extremities were cleaved at a slight angle, the fiber design was improved to limit backscattering, and most importantly optical isolators were integrated in laser packages.

In the mid-IR, although QCLs are much more resistant to optical feedback than their interband counterparts due to the lower α-factor,[6] it has been shown that they still exhibit the same behavior in terms of changes of output power, threshold current and optical spectrum.[7] Furthermore, chaotic emission from a QCL under optical feedback has recently been evidenced.[8] Therefore, it is necessary

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to quantify the optical feedback originating from a mid-IR fiber to know how much a QCL operation will differ between free-space and fibered characterizations.

Optical feedback is known to have a significant impact on the laser threshold. The rate equations of a QCL operating under optical feedback due to reflections on either a mirror or a fiber tip can indeed be written as:

$$\frac{dN_3}{dt} = \eta \frac{I}{q} - \frac{N_3}{\tau_{32}} - \frac{N_3}{\tau_{31}} - G_0 \Delta N S \tag{1}$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} + G_0 \Delta N S \tag{2}$$

$$\frac{dN_1}{dt} = \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_{21}} - \frac{N_1}{\tau_{out}} \tag{3}$$

$$\frac{dS}{dt} = \left(N_{pd} G_0 \Delta N - \frac{1}{\tau_p} \right) S + \beta N_{pd} \frac{N_3}{\tau_{sp}} + 2k\sqrt{S(t)S(t-\tau_{ext})}\cos(\Delta\phi) \tag{4}$$

$$\frac{d\phi}{dt} = \frac{\alpha}{2} \left(N_{pd} G_0 \Delta N - \frac{1}{\tau_p} \right) - k\sqrt{\frac{S(t-\tau_{ext})}{S(t)}}\sin(\Delta\phi) \tag{5}$$

where S is the photon density, ϕ the phase of the electric field, N_j is the carrier density of level j, $\Delta N = N_3 - N_2$. η is the conversion efficiency, I is the bias current. τ_{ij} corresponds to the carrier lifetime from level i to level j, τ_{out} is the characteristic time for the electron to tunnel into the injector, τ_{sp} is the spontaneous emission lifetime, τ_p is the photon lifetime inside the laser cavity. N_{pd} is the number of periods and G_0 corresponds to the net modal gain for one period, α to the linewidth enhancement factor (LEF) and β to the spontaneous emission coefficient. $\Delta\phi$ is defined as $\Delta\phi = \omega_0 \tau_{ext} + \phi(t) - \phi(t - \tau_{ext})$, with ω_0 the free-running angular frequency and τ_{ext} the external cavity roundtrip time. Finally, k is the feedback coefficient, defined as:

$$k = \frac{1}{\tau_{in}} \frac{1 - R_2}{\sqrt{R_2}} \sqrt{f_{ext}} \tag{6}$$

with τ_{in} the internal cavity roundtrip time and R_2 the reflectivity of the laser facet directed toward the external cavity. In the previous equations, we can neglect the spontaneous emission term, since its characteristic time is three orders of magnitude shorter than other lifetimes.

From eq. 1 to 5 under steady-state, the threshold reduction under optical feedback can be expressed as:

$$I_{th} = \frac{q}{\eta} \frac{\tau_{32} + \tau_{31}}{\tau_{31}(\tau_{32} - \tau_{21})} \frac{1}{N_{pd} G_0} \left[\frac{1}{\tau_p} - 2k\cos(\omega_s \tau_{ext}) \right] \tag{7}$$

where ω_s is the wavelength of the QCL under optical feedback, corresponding to:

$$\omega_s - \omega_0 = -k \left[\alpha \cos(\omega_s \tau_{ext}) + \sin(\omega_s \tau_{ext}) \right] \tag{8}$$

with α the linewidth enhancement factor.

The QCLs under study are Fabry Perot (FP) lasers emitting around 5.6 μm. The active area consists in 30 periods of AlInAs/GaInAs, inserted between two InP claddings. A high-reflection coating was added on the back facet for CW operation. The lasers are 6 μm wide and 3 or 4 mm long. The 3 mm-long laser is operated at 20°C, its threshold is at 668 mA and 9.64 V, and the maximum output power is around 50 mW. The 4 mm-long QCL has a threshold at 799 mA and 9.50V at 15°C, with a maximum power of 30 mW.

All parameter values for this specific QCL structure are summarized in Table I, except the conversion efficiency η, which is used as a fitting parameter to obtain the correct free-running threshold current. These values have been calculated using a homemade heterostructure simulation software, METIS, based on semi-classical Boltzmann-like equations with thermalized subbands. It enables the calculation of potential, energy states, electronic scattering times and wave functions, as presented in Figure 1.

The 1 m-long optical fiber used for the experiments is fabricated from the chalcogenide glass $As_{38}Se_{62}$. Before drawing, the preform has been elaborated by a molding method as described in

TABLE I. Laser parameters

Parameter	**Value**	**Parameter**	**Value**
α	1.3	N_{pd}	30
τ_{32}	2.27 ps	n_g	3.2
τ_{31}	2.30 ps	R_2	0.3
τ_{21}	0.37 ps	G_0	1.2×10^4 s^{-1}
τ_{out}	0.54 ps	τ_p	4.74 ps

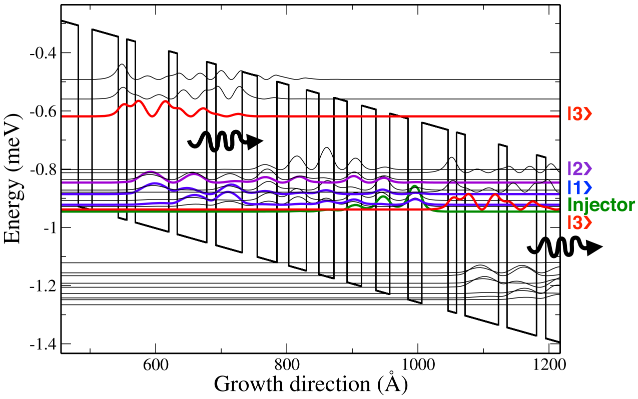

FIG. 1. Wave functions of the QCL structure under study, simulated with METIS. In red, levels 3 of two consecutive periods, in violet level 2, in blue level 1 split in two phonon states, in green injector state. The back arrows show the photon emission.

Ref. 3. Briefly, this method consists in heating up the chalcogenide glass rod and in letting it flow into a silica mold whose design corresponds to the negative shape of the final preform. Then the perform is placed in a silica enclosure under helium flowing and heated thanks to an annular electrical furnace. During fiber drawing, the hole diameters are controlled by applying an inert gas (He) pressure in the holes of the preform. The insert in Figure 2 presents a section of the fiber. It consists of a microstructured fiber constituted of 36 holes with an outer diameter of 120 μm and a central solid core of 12 μm. Besides, its attenuation is below 1 dB/m from 3 to 9.6 μm, except an absorption peak around 4.6 μm corresponding to the Se-H band, as shown in Figure 2.

Optical feedback experiments in a 15 cm long free-space external cavity were performed with the 4 mm long QCL in order to verify the theoretical results. Details on the experimental setup can

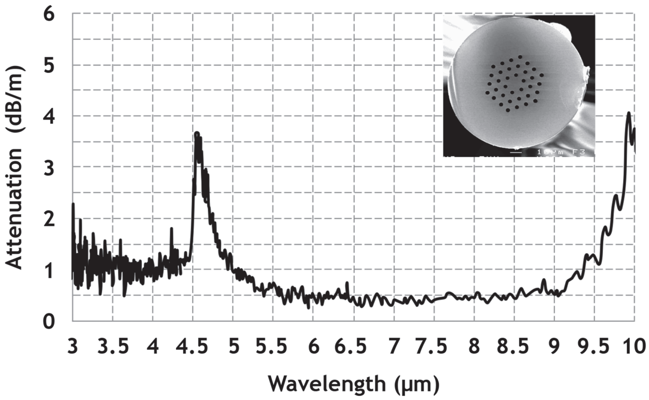

FIG. 2. Attenuation of the fiber core as a function of the wavelength. Insert: cross-section of the chalcogenide microstructured optical fiber.

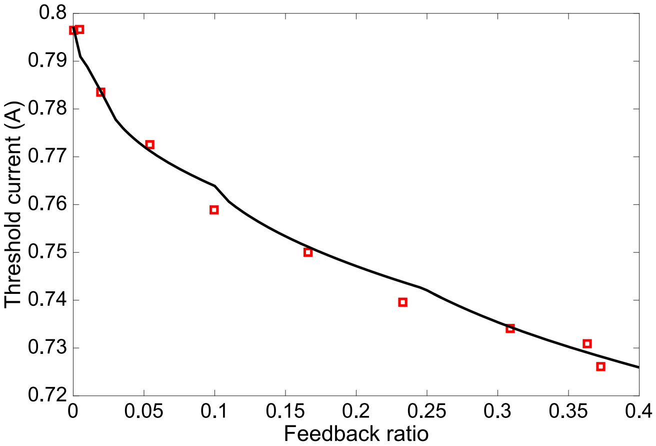

FIG. 3. Threshold reduction with optical feedback for $L_{ext} = 25$ cm, experimental data (red squares) and numerical simulation (black solid line).

be found in Ref. 7. The L-I curve of the QCL was measured and the threshold current extracted for various feedback ratios. Fig. 3 represents the evolution of the threshold current of the QCL as a function of the feedback ratio, showing very good agreement with theoretical predictions computed from Eq. 7.

In order to estimate the strength of the optical feedback originating from chalcogenide fibers, the fiber was used to collect the light from a 3 mm-long QCL and threshold measurements of the laser were performed using the optical power at the other end of the fiber. The optical fiber was placed directly at the output of the 3 mm-long QCL and the alignement was performed by maximizing the optical power measured at the fiber output. The cavity length between the QCL facet and the fiber tip was estimated around 200 μm. Comparison between measured and calculated threshold currents using Eq. 7 then allows estimating the strength of the optical feedback induced by the fiber.

Fig. 4 shows the theoretical threshold reduction with feedback strength, along with two sets of measurements of the QCL threshold current. A first set of measurements gave threshold currents close to 0.65 A, leading to an estimated feedback ratio from the fiber of $f_{ext} = 11\% \pm 1\%$, the uncertainty being obtained from repeating the fiber alignment and L-I measurements. A second set of measurements was performed after a cleaner cleavage inducing a better coupling of the laser light into the fiber, which led to a slightly reduced threshold current compared to the first set and a corresponding feedback ratio of $f_{ext} = 15\% \pm 1\%$.

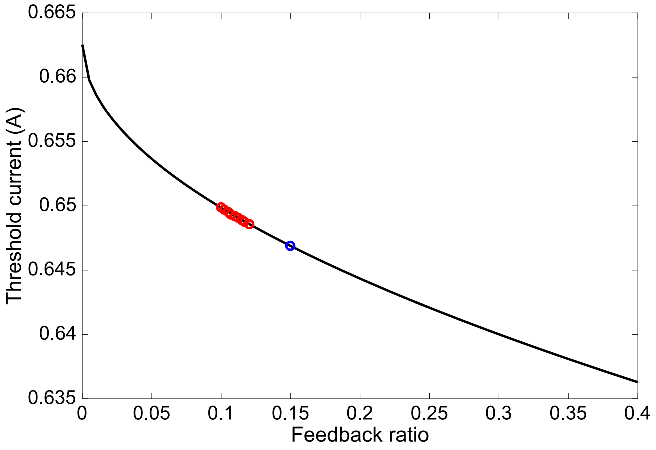

FIG. 4. Optical feedback from a mid-IR fiber. Solid line: simulation of threshold reduction. Red dots: first set of measurements. Blue dot: second set of measurements after better cleavage of the front facet of the fiber.

These results show that a significant portion of the light emitted by the QCL is reflected by the fiber, originating at least from the fiber facet. With a refractive index around 2.77, almost twice that of near-IR optical fibers, the optical interface created by a cleaved chalcogenide fiber can indeed reflect up to 22 % of the light back to the QCL, depending on the distance to the laser facet and the beam divergence. Since the expression of threshold reduction obtained from Eq. 7 shows little variation with the external cavity length, we cannot use it to determine whether the feedback originates only from reflections at the fiber tip or if internal backscattering also plays a role.

This significant amount of optical feedback originating from back-reflections on a mid-IR fiber could affect the emission properties and the stability of the fibered QCL. In previous studies, the analysis of the optical spectra of a distributed feedback (DFB)-QCL under optical feedback allowed mapping the regimes of a QCL under feedback, corresponding alternatively to single- or multimode, stable or unstable operation.[7] The unstable regime was furthermore proven to correspond to a temporal chaos.[8] The amount of feedback necessary to destabilize the QCL varies strongly depending on the laser characteristics, including the active material and its design or dimensions. For the specific QCL considered here, based on an analysis of the feedback regimes from the optical spectra, chaotic operation is observed for feedback ratios between 18% and 24%. Therefore, the feedback ratios estimated in this study are not sufficient to render the laser unstable by simply coupling their light using a fiber.

However, another QCL device could present a lower threshold to destabilization and be affected by the use of this fiber. For instance, the DFB-QCL studied in Ref. 7 is based on the same active area than the Fabry-Perot considered here, but has a much lower tolerance threshold of 13%, due to the existence of the DFB grating. Therefore it is to be expected that, for some QCLs, the use of a chalcogenide fiber can destabilize the laser.

To reduce the amount of optical feedback back-reflected from a chalcogenide fiber in a mid-IR QCL, a mere tilt in the fiber cleavage would allow diverting the reflected light away from the QCL facet. The addition of an anti-reflective coating could also be considered. Proper knowledge and control of back-scattering along the fiber is also necessary to further reduce reflections. Furthermore, the development of compact mid-IR optical isolators that could be integrated in laser packages would be crucial for applications of fibered QCL such as long distance gas spectroscopy.

A theoretical and experimental study of threshold reduction in QCLs subject to external-cavity optical feedback was used to estimate the strength of the optical feedback originating from a chalcogenide fiber used to couple the emitted light. Feedback strengths between 11 and 15 % were estimated using different straight fiber cleavages, showing the influence of reflections from the fiber tip. This amount of feedback could be sufficient to deteriorate the emission properties of some QCL devices and must be avoided.

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