Gain enhancement in a terahertz quantum cascade laser with parylene antireflection coatings

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We study the effect of parylene antireflection coatings on the gain of a 2.8 THz quantum cascade laser using terahertz time-domain spectroscopy. With antireflection coatings the threshold current increases as the mirror losses are increased, and the gain clamps at 16 cm^{-1}, compared to 10 cm^{-1} for an uncoated device. These values are consistent with a drop in reflectivity from 0.320 to 0.053 as a consequence of the coating deposition. Further improvements could reveal the bare cavity gain and permit the quantum cascade laser to be used as an efficient terahertz amplifier. © *2011 American Institute of Physics*. [doi:10.1063/1.3562002]

Terahertz (THz) quantum cascade lasers (QCLs) have been used as gain media for external-cavity lasers[1] and as amplifiers for THz waves.[2,3] For these applications the bare cavity gain, i.e., the gain in the absence of the laser field, needs to be accessed. However, when laser action occurs, the gain clamps to the total losses, thus limiting the attainable amplification.[4] Recently, ultrafast gain switching[5] and phase seeding[6] with short electrical pulses have been used to access the bare cavity gain. These dynamic amplification techniques require synchronization between the electrical pulse and the THz pulse to be amplified. On the other hand, the bare cavity gain can be accessed in the steady-state simply by increasing the mirror losses via a reduction in the facet reflectivity. This is commonly achieved by applying antireflection (AR) coatings on the laser's facets. Assuming lasing in the cavity and a weak externally coupled input radiation, the amplification factor is given by[7]

$$\frac{E_{\mathrm{out}}(\omega)}{E_{\mathrm{in}}(\omega)} = \frac{T}{\sqrt{R}}, \qquad (1)$$

where ω is the laser frequency, E_{in} and E_{out} are the input and output electric fields, R is the facet reflectivity, and T is the transmittance. A different approach to access the bare cavity gain is by fabricating tilted facets. Nevertheless, the advantage of AR coating is in particular that the output beam is not distorted.

In this work, THz time-domain spectroscopy (TDS) is used to investigate the gain of a QCL with and without AR coatings. The facets of a QCL are coated with parylene C (poly-monochoro-para-xylene) which has been used as AR coating at THz frequencies for silicon passive optics.[8,9] Indeed parylene C presents several properties that make it an attractive choice as an AR coating, namely, a good thermal stability, together with good adhesion and low absorption at THz frequencies. Furthermore, it is deposited at room temperature and commonly used as a hydrophobic encapsulation film for electronic circuit boards.

An AR coated facet gives zero reflectivity if its refractive index, n_{AR}, and its thickness, d, satisfy the following conditions: (i) $n_{\mathrm{AR}}=\sqrt{n}$, and (ii) $d=m\lambda/4n_{\mathrm{AR}}$. Here n is the refractive index of the laser cavity, m is an odd integer, and λ is the wavelength. The refractive index of a QCL operating around 3 THz is $\sim$3.6, therefore n_{AR} should be equal to 1.9. The THz index of parylene (1.62) (Ref. 8) is close to this ideal value. Regarding condition (ii), the thickness of the AR coating will be between 10 and 20 μm for frequencies in the 4.61 to 2.31 THz range. An alternative to parylene for AR coatings is SiO_2 (fused silica). The advantage of this material is that its index of refraction can be made closer to the ideal value, i.e., between 1.9 and 2.1 depending on the coating process.[1,10] SiO_2 has been used as an AR coating film on one facet of a 4.8 THz-QCL to suppress laser action in the demonstration of an external-cavity THz QCL.[1] The drawback of SiO_2 is in the difficulty of realizing the thick layers needed for THz AR coatings. Indeed, the thickness of SiO_2 must be larger than 10 μm for frequencies lower than 3.9 THz. In contrast, robust thick coatings, of thickness larger than 10 μm, can be routinely produced with parylene.

In order to investigate the effects of AR coatings on THz QCLs we used two nominally identical 2.8 THz lasers from the same wafer. One device was AR coated with parylene, while the other was left uncoated and used as a reference. The active region of the QCLs was based on a bound-to-continuum design.[11] Devices were fabricated in a single plasmon waveguide geometry, and cleaved into 3 mm long, 240 μm wide Fabry–Perot ridge-cavities. The AR coated device was covered with a 17-μm-thick parylene film using a chemical evaporation deposition technique, under vacuum and at room temperature, performed by a commercial company (Comelec SA). As the coating deposition is isotropic, at the end of the process parylene covers all surfaces, therefore the QCL was previously wire bonded in order to ensure electrical contacts. All measurements were performed at 4.5 K. During the experiments, the coatings experienced several thermal cycles between room temperature and 4.5 K without apparent deleterious effects on their mechanical properties (i.e., adherence, surface quality etc.). Voltage-current density

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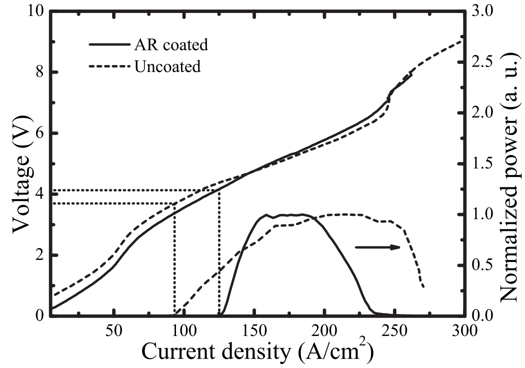

FIG. 1. Voltage and normalized output power as a function of current density of the uncoated (dashed lines) and AR coated (solid lines) QCLs at 4.5 K. The lasers were operated at 10 kHz with a duty cycle of 20%. For light- current measurements the 10 kHz pulse train was modulated at 20 Hz to enable detection using a standard pyroelectric detector. The laser threshold for the uncoated QCL was 90 A/cm^2. For the AR coated device the threshold increased to 124 A/cm^2.

$(V-J)$ and light-current density $(L-J)$ characteristics of the AR coated and uncoated devices are shown in Fig. 1. The optical power was measured with a standard pyroelectric detector. The devices present similar $V-J$ characteristics, while for the $L-J$ curves we observe a clear increase in the threshold current from 90 to 124 A/cm^2. The AR coated laser shuts off at lower current. This is because the laser action stops when the gain becomes smaller than the losses which are higher in the AR-coated sample.

The QCL gain was characterized using TDS where broadband THz pulses from an interdigitated photoconductive antenna[12] were coupled into the laser cavity.[4] A Ti:sapphire laser operating at 76 MHz was used as a femtosecond pulse source for THz pulse generation and detection. The amplitude and phase of the transmitted pulses were detected using electro-optic sampling. The electro-optic crystal was a 200-μm-thick $\langle 110 \rangle$ ZnTe crystal, attached to a nonactive 2-mm-thick ZnTe crystal. The normalized time-dependent electric field amplitude of the transmitted THz pulses from the coated and uncoated QCLs are plotted in Fig. 2(a). The devices were operated at 164 A/cm^2, i.e., above laser threshold. It appears clearly that electric field oscillations persist for a longer time in the AR coated device, which corresponds to a narrower spectrum in the frequency domain. The spectral gain of the QCL is calculated by normalizing the Fourier amplitude of the waveform in Fig. 2(a) to that of the waveform at zero bias voltage (see Ref. 4 for more details). The spectral gain of both devices operated at 164 A/cm^2 in Fig. 2(b) shows that the input THz pulse experiences a higher gain in the coated QCL. The gain spectrum of the coated laser is narrower than that of the uncoated laser as the gain clamps at higher current.[13] During lasing action the gain bandwidth is found to decrease with increasing current density because of the coupling between states in the injector with the upper laser state. The dip around 3 THz of the AR coating gain spectrum is due to reference signal dropping off at this frequency.

The transmitted THz pulses were measured at different applied currents and Fig. 3 shows, for the two devices, the evolution of the gain at 2.8 THz as a function of current density. With AR coating the gain, G_{co}, clamps at approximately 16 cm^{-1}, whereas the value of the clamped gain of the uncoated laser, G_{unco}, is approximately 10 cm^{-1}. The fact

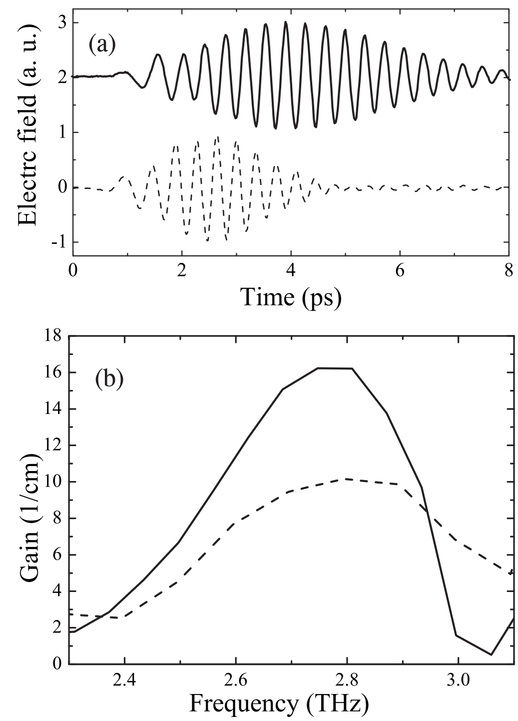

FIG. 2. (a) Normalized electric fields of THz pulse transmitted through the uncoated (dashed line) and AR coated (solid line) QCL operated at 164 A/cm^2 (above threshold). An offset is added for clarity. (b) Gain spectra of the lasers taken at 164 A/cm^2.

that gain clamping is still occurring for the coated sample indicates that the reflectivity of the facet is not sufficiently low to completely suppress lasing.

The reflectivity of the coated facet can be obtained by recalling that the value of the clamped gain is equal to the total losses, $G=\alpha_m+\alpha_w$ (mirror and waveguide losses, respectively). The waveguide losses of both coated and uncoated lasers are equal since the devices come from the same wafer. For the mirror losses we have $\alpha_m=\ln(1/R)/L$ where L is the cavity length and R the reflectivity. Using a facet reflectivity of $R\sim 0.32$ (Ref. 14) for the uncoated device gives $\alpha_m=3.8$ cm^{-1}. Therefore, from the clamped gain of the uncoated laser, we obtain $\alpha_w=6.2$ cm^{-1} (in agreement with simulations). From this value we can deduce the mirror losses of the coated facet, $G_{co}-\alpha_w=9.8$ cm^{-1}, which gives a reflectivity of 0.053 ± 0.007. The errors are estimated from the clamped gain uncertainty of 0.5 cm^{-1}. The reflectivity of

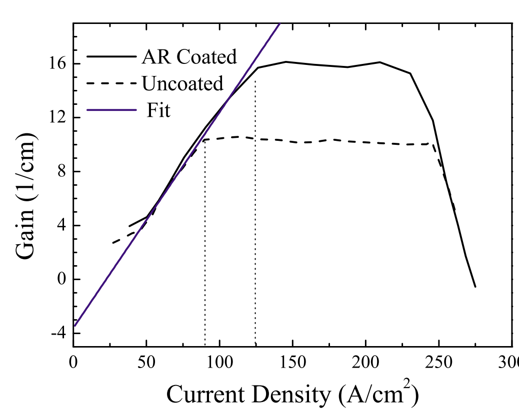

FIG. 3. (Color online) Gain of the uncoated and AR coated QCLs as a function of current density at 2.8 THz. The dotted lines are eye guides representing the laser thresholds and clamped gains. The straight solid line (blue) is a linear fit to the gain, G, below threshold.

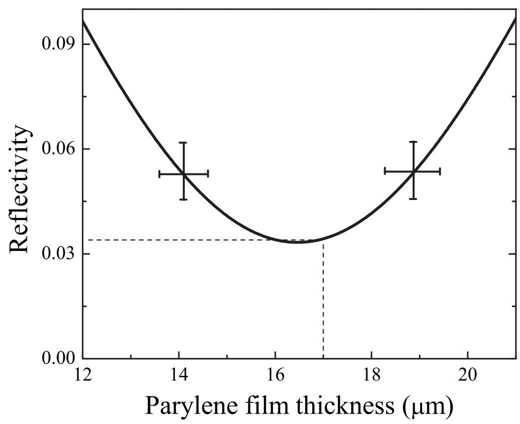

FIG. 4. Calculated reflectivity as a function of parylene film thickness coated on the facet of a QCL operating at 2.8 THz. The calculation is based on Fresnel coefficients. The refractive indices of the laser and parylene film are 3.6 and 1.62, respectively. The absorption coefficient of the coating film, i.e., 16 cm^{-1}, is taken into account. Dashed lines are eye guides showing the reflectivity of the 17 μm thick film which was fabricated on the QCL and error bars are a guide to the thicknesses of the film corresponding to the reflectivity of 0.053 determined from the clamped gain. The error bars are calculated from the clamped gain uncertainly of 0.5 cm^{-1}.

the coated facet as a function of AR coating thickness can be simulated using an approach based on plane-wave Fresnel coefficients.[15] The calculation takes into account the absorption coefficient of parylene (16 cm^{-1}) at 2.8 THz.[16] The result is shown in Fig. 4. The minimum reflectivity of 0.033 is found for a film thickness $d=16.5$ μm. The simulated reflectivity that corresponds to the used thickness of 17 μm is 0.034. As can be seen from the graph, the reflectivity increases rapidly with the coating thickness. The fact that the experimental reflectivity computed from the clamped gain is higher than the theoretical value might originate from the deposited film being thinner or thicker than 17 μm due to the effect of the edge of the QCL ridge. Indeed the AR coating thickness of 17 μm was measured after the coating process on a calibration wafer using a profilometer (16.5 μm was the targeted thickness). The calibration wafer was positioned horizontally, i.e., normal to the laser facet plane. This fact, together with the different surface geometry, has possibly produced a different thicknesses being deposited on the laser facet. From Fig. 4, the parylene thicknesses corresponding to the obtained reflectivity of 0.053 are 14.1 and 18.9 μm.

The consistency of our results can be checked by calculating the ratio of the threshold currents in Fig. 1 and comparing them with the measure gain values in Fig. 3. From Fig. 3 we can see that the gain just below threshold can be approximated by a straight line with a nonzero y-intercept. Thus the subthreshold gain G in Fig. 3 can be expressed as $G=gJ+b$ where J is the current density, g is the gain coefficient (units A/cm), and b is a constant corresponding to the y-intercept. From the fit in Fig. 3, $g=0.16$ A/cm and $b=-3.6$ cm^{-1}. The ratio of the threshold currents in Fig. 3 can then be obtained as $J_{co,th}/J_{unco,th}=(G_{co,th}-b)/(G_{unco,th}-b)$. Here, $J_{co,th}$, $J_{unco,th}$, and $G_{co,th}$, $G_{unco,th}$ are the values on the threshold currents and of the clamped gains for the coated and the uncoated device respectively. From the clamped gain values, the right side of the previous expression=1.44, which is very close to the ratio of the threshold currents, i.e., 124/90=1.38.

It should be noted that one method to determine the waveguide losses in QCLs consists is plotting the threshold current as a function of the mirror losses for devices of different lengths (see, for example, Ref. 17). This technique assumes implicitly that G is proportional to the current density with a zero y-intercept, i.e., $b=0$. Physically this means that the QCL has a zero transparency current.[18] As shown above such *a priori* assumption is not necessary for the determination of the waveguide losses when the gain is measured using the time-domain technique.

In conclusion, THz-TDS has been used to investigate the effect of parylene AR coatings on the gain of QCLs. Although the decrease in reflectivity produced by the AR coating was not sufficiently low to completely suppress laser oscillations, the value of the clamped gain increased from 10 to 16 cm^{-1} from an uncoated to an AR coated device. This is consistent with a reduction in the facet reflectivity from 0.320 to 0.053 and in agreement with the observed increase in threshold current. Further studies will concentrate on reducing the reflectivity further by optimizing the AR coating thickness in order to maximize the amplification as well as to access the bare cavity gain.

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