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Single mode terahertz quantum cascade amplifier

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A terahertz (THz) optical amplifier based on a 2.9 THz quantum cascade laser (QCL) structure has been demonstrated. By depositing an antireflective coating on the QCL facet, the laser mirror losses are enhanced to fully suppress the lasing action, creating a THz quantum cascade (QC) amplifier. Terahertz radiation amplification has been obtained, by coupling a separate multi-mode THz QCL of the same active region design to the QC amplifier. A bare cavity gain is achieved and shows excellent agreement with the lasing spectrum from the original QCL without the antireflective coating. Furthermore, a maximum optical gain of ∼30 dB with single-mode radiation output is demonstrated. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4897438]

Quantum cascade lasers[1] (QCLs), based on light emission driven from electron transitions between individual subbands within the conduction band, have been proven to be a compact coherent signal source in terahertz (THz) spectral region, playing a vital role in many applications such as metrology,[2] imaging,[3] and also high-resolution spectroscopy.[4] Furthermore, this device concept could be extended, in principle, to an optical amplifier, to fulfill applications where coherent radiation with high signal to noise ratio are required. In fact such devices have already been demonstrated in the master-oscillator power amplifier scheme[5] as well as a gain-switched amplifier for ultrafast pulses.[6] For the master-oscillator power-amplifier scheme, an angled front facet was utilised to minimise facet reflections. This scheme is far from optimal, since the angled facet deforms the wavefront as well as the beam quality, resulting in a severely astigmatic beam. The gain-switched amplifier scheme is based on the fact that the time for turning on the gain of the laser is much faster than the build up time for the laser field, so that the gain clamping effect is avoided. However, this approach would only allow the amplification of short pulses. So, in principle, the straightforward way to achieve a quantum cascade (QC) amplifier would require a proper antireflective (AR) coating on the facet to fully suppress the feedback, thus the bare cavity gain could be exploited. However, in the terahertz frequency region, due to relatively long wavelengths (∼100 μm) very few materials with dedicated refractive indices as well as low absorption features are available to produce optimal AR coatings. Until now, two approaches have been demonstrated for AR coating on THz QCL structures. First, in an external cavity tuning configuration, implemented with SiO_2 as AR coating layer on the QCL facet, the facet reflectivity was fully suppressed.[7] However, due to the difficulty with producing reliably thick films (>10 μm), it has only been realized at relatively short wavelengths, 4.7 THz in this case. Second, parylene C (poly-monochoro-para-xylene) was characterized as an AR coating layer to enhance the clamped gain of a QCL.[8] In this case, due to non-optimal coating thickness, the facet reflectivity of a 2.9 THz QCL was only reduced down to about 5%. As a result, the bare cavity gain was not achieved due to the residues of the facet reflection, as the cavity gain only clamped to the total losses where the lasing action occurs.

In this paper, by fully optimizing the parylene C antireflective coating on a 2.9 THz QCL device, we have developed a QC amplifier by fully suppressing its lasing action. By coupling it with a separate THz QCL, based on the same active region design acting as the seeding THz source, an amplification in THz radiation was observed. We studied the gain characteristics of the QC amplifier at different seeding intensity levels. Also the output spectra from the device were analysed.

According to the Fresnel expression, an antireflective layer is obtained when its refractive index n_{AR}, and thickness d, satisfy the conditions $n_{AR} = \sqrt{n_a n_b}$ and $d = (2m+1)\lambda/4n_{AR}$ such that the reflection at the interface is suppressed to zero. Here, the n_a and n_b are the refractive indices for two optical materials, m is an integer and λ is the wavelength. Since the refractive index of a terahertz QCL is about 3.6,[9] the optimal choice of the antireflective material holds a refractive index ∼1.9. As a result, SiO_2 with a refractive index between 1.9 and 2.1 depending on the processing conditions is an ideal AR coating on a THz QCL. As described in Ref. 7, an external cavity coupled QCL operating at 4.7 THz was demonstrated with an 8.3 μm thick SiO_2 layer deposited on the laser facets, where the lasing action was fully suppressed due to the improved facet reflectivity. However, as the frequency is reduced, even thicker SiO_2, with more than 10 μm is required, which is difficult to achieve practically. Consequently, parylene has been shown to be a promising AR coating material due to its good thermal and mechanical stability together with its low absorption feature in the terahertz frequency region.[8] Despite the fact that the refractive index of parylene C is about 1.62, close to the optimal value 1.9, the minimal reflectivity from a QCL-air interface with an optimal thickness of parylene C coating is calculated to be ∼2%; this is low enough to overcome the material gain with relatively short device lengths. As demonstrated in Ref. 8, with a non-optimal parylene C coating,

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the facet reflectivity was reduced to 5.3% on a 2.9 THz QCL. Although the laser gain was enhanced from 10 cm^{-1} to 16 cm^{-1}, the threshold current was not fully suppressed, as the lasing oscillation was still observed. In this work, for purpose of a terahertz optical amplifier, we have optimized the antireflective coating with parylene C at 3 THz, where the optimal thickness is calculated to be about 15.5 μm. The coating deposition was performed by a commercial company (Metal Improvement Company, Ireland) with a growth rate about 0.2 ~ 0.3 μm per minute and a deposition accuracy of ±1 μm. The layer is applied by vapour deposition under vacuum conditions at room temperature such that the parylene condenses and polymerizes on the surface of the object in a polycrystalline formation. Three devices with the same active region design were fabricated and processed for coating deposition with targeting thicknesses of 16, 17, and 18 μm, where actual coating thicknesses measured from planar GaAs chips coated during the same process run were 16.6, 17.7, and 18.5 μm, respectively. At the end, the 17.7 μm coating device showed fully suppressed lasing action. The other two QCLs still showed weak lasing but with increased threshold current and consequently had a decreased dynamic range. The discrepancy between the measured (17.7 μm) and the calculated (15.5 μm) optimal thickness we believe originate from the fact that the deposition rate varies on the laser facet compared with the planar dummy chip, which at the end results in a thinner coating layer on the facet.

The THz QC amplifier sample used for this work is based on a 2.9 THz active region material with the bound-to-continuum design as described in Ref. 10. 90 repeat periods of a GaAs/$Al_{0.15}Ga_{0.85}As$ heterostructure were grown by molecular beam epitaxy, and the device was fabricated into a single plasmon geometry by wet etching and cleaved into a 250 μm wide, 1.33 mm long Fabry-Pérot ridge cavity. All the measurements were performed at 4.5 K in a flow-helium cryostat, and the power was collected by a standard Golay cell detector, and then recorded by a lock-in amplifier in mV. The voltage and emitted light intensity as a function of current are shown for the QC amplifier device with and without antireflective coating in Fig. 1. As it can be seen, the device presents similar current-voltage characteristics, while for the current-intensity plots, the AR coated case shows non-lasing action. This clearly indicates with an optimal antireflective coating on the facet, the enhancement of the mirror losses fully suppresses the lasing oscillation, which provides a terahertz amplifier at 2.9 THz based on the quantum cascade laser structure.

The QC amplifier was characterized by directly coupling to a separate seeding THz QCL, which was fabricated from the same batch with the same active region design at a length of 1.82 mm. As the seeding emitter, the QCL was coupled to the amplifier face to face by mounting them together on the cold plate as shown in Fig. 2(a), where the transverse-magnetic (TM) polarized radiation was directly coupled into the QC amplifier cavity. The spacing distance between the seeding laser facet to the amplifier facet is ~500 μm, which was chosen as a balance between maintaining beam coupling efficiency and not disrupting the non-lasing condition of the amplifier. Since as demonstrated in Ref. 7, a gold mirror as a reflector mounted directly in front of the laser cavity with a spacing distance less than 200 μm could provide enough feedback to the laser cavity to tune the frequency. However, for the seeding QCL, the threshold current was reduced from 136 A/cm^2 with the coupled QC amplifier unbiased to 120 A/cm^2 with the coupled QC amplifier biased to the roll-off point. All the measurements were performed in pulsed

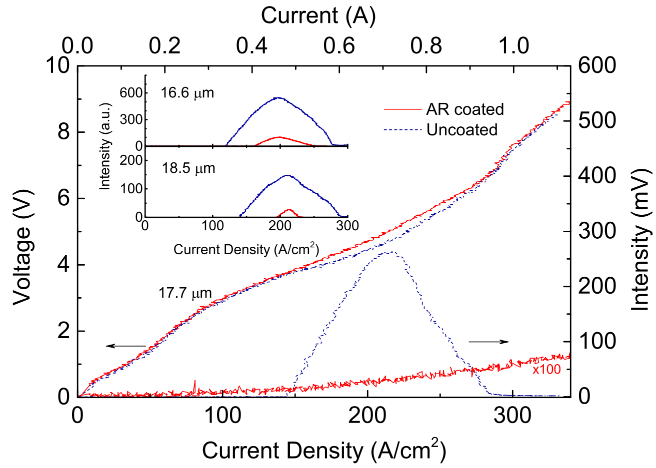

FIG. 1. Voltage and output intensity as a function of the current density for the QC amplifier with (red line) and without (blue dashed line) antireflective coating. The inset picture shows output intensity curves as a function of the current density for the QCL with 16.6 μm and 18.5 μm parylene C coating, respectively, with (red line) and without (blue dashed line) antireflective coating. All the measurements were performed at 4.5 K.

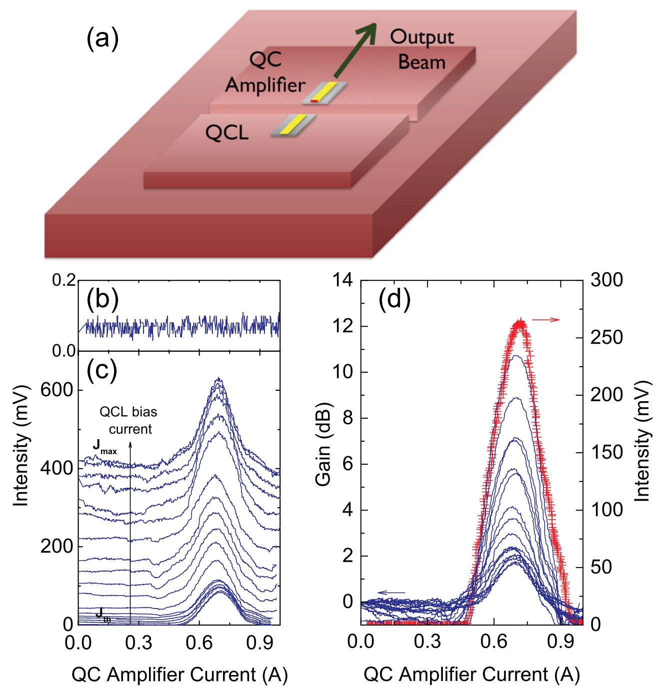

FIG. 2. (a) Schematic drawing of the measurement setup. A seeding THz QCL is placed directly in front of the QC amplifier, with a spacing distance ~500 μm, where the radiation is coupled into the QC amplifier then amplified and measured from the uncoupled facet. (b) QC amplifier output intensity as a function of its bias current when the coupled QCL is biased below J_th. (c) QC amplifier output intensity as a function of its bias current at different input intensities from the seeding QCL. The seeding intensity was varied with the QCL bias field. (d) Normalized optical gain of the QC amplifier as a function of its bias current at different input intensities (blue curve). On the right axis, the measured output intensity of the QC amplifier without the antireflective coating is shown (red cross).

mode with a 10 kHz repetition rate and a 15% and 20% duty cycle for the seeding QCL and QC amplifier, respectively. Slightly longer pulses for the QC amplifier were used to ensure the two devices were excited simultaneously with maximum overlap. To evaluate the amplification, we examined the output intensity from the QC amplifier as a function of its driving current, at different seeding intensities from the QCL. As plotted in Fig. 2(c), the seeding intensity from the QCL, measured with an unbiased QC amplifier (0 A as shown in the plot), increased as a function of its driving current. By keeping the seeding QCL bias field constant but varying the driving current of the QC amplifier, the output intensity from the device showed amplification due to the bare cavity gain from the QC amplifier. Evidence of the gain was observed for driving current of the QC amplifier above 0.45 A, where the device exhibited pronounced single-pass amplification behaviour. Above this current, the amplification increased as the bias field became higher. Small reduction in the intensity at lower bias current before the amplification was also observed. This could be attributed to resonant absorption from the injection level into the lower lasing levels in the QC amplifier.

By calculating the amplification $10\log(P_{out}/P_{in})$, we can extract the optical gain for the QC amplifier. In Fig. 2(d), the optical gain was plotted as a function of the bias current at different seeding intensities from the QCL. As expected, the peak gain point from the QC amplifier was obtained at the roll-off current of 0.7 A, which corresponded to the roll-off current measured before the device was coated. The gain region corresponded with the dynamic range of the device without the coating as well. Furthermore, the peak gain at each seeding power level was summarized in Fig. 3(a) by recording the optical gain at the roll-off current as well as the input intensities. It can be seen that the peak gain decays exponentially with the input intensity. At very low input intensity levels, the peak gain could reach up to ∼30 dB; while at the maximum seeding input intensity level, the peak gain stays at ∼1.7 dB. This amplification is in reasonable agreement with the expected amplification of 2 times.[5] Moreover, by plotting the output intensity of the QC amplifier with respect to the input intensity of the seeding QCL at the roll-off current, we can clearly see that the output intensity linearly increases as a function of the seeding intensity. The enhanced intensity also went from 100 mV to about 225 mV with the increase of the input intensity, which was still lower than value of 250 mV (the output intensity measured from the amplifier before coated). All these facts suggest that the QC amplifier had not yet been saturated.

We have also examined the output spectra with a constant seeding intensity at different QC amplifier biases. As shown in Fig. 4, the spectrum measured with the QC amplifier unbiased indicated the output spectrum due to the seeding QCL only. It shows a multi-mode spectrum with a mode spacing of 22 GHz, which corresponds to the mode spacing due to the Fabry-Pérot cavity of the seeding QCL. With the increase of the output intensity as more amplification from the QC amplifier at higher bias fields, the main mode at 2.926 THz was more pronounced with further suppression over the other modes. At the roll-off current of the QC amplifier, the device behaved like a single mode filter where a single mode emission was achieved, with a single mode suppression ratio of 20 dB. This could be understood by the gain narrowing effect, which has been observed in a bound-to-continuum QCL structure.[11] For the low bias field, several highly coupled upper laser levels contribute to the lasing transition simultaneously. The multi-transitions induce broadening of the gain spectra. However, as the applied bias increases, the injector miniband is shifted to higher energy states with respect to the upper laser levels, so a smaller number of upper laser levels are coupled. Until at the end, it will reach to a point where only one single upper laser level contributes to the lasing transition, which provides a narrower gain spectrum. Furthermore, the gain from the QC amplifier also increases at higher bias fields before the roll-off current. Since the active region of the QC amplifier

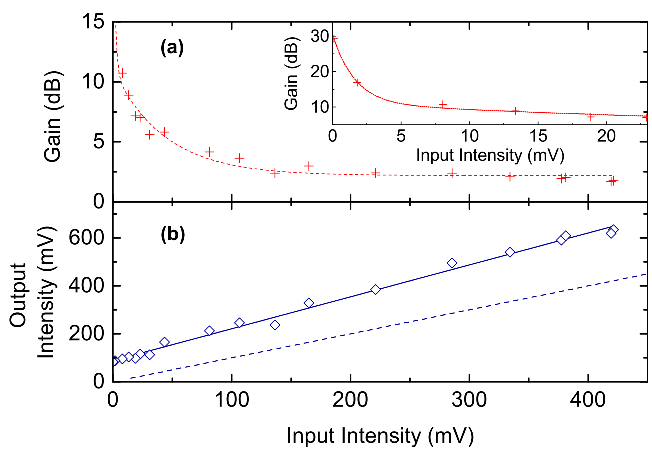

FIG. 3. (a) Peak gain from the QC amplifier at the roll-off bias point (0.7 A) as a function of the input intensity (red cross). The dashed line is an exponential fit to the peak gain curve. The inset shows the peak gain at low input intensity region. (b) The total output intensity from the QC amplifier with respect to the input intensity (blue square). The dashed line is the guideline for the input intensity value only, and the straight solid line is a linear fit to the output intensity.

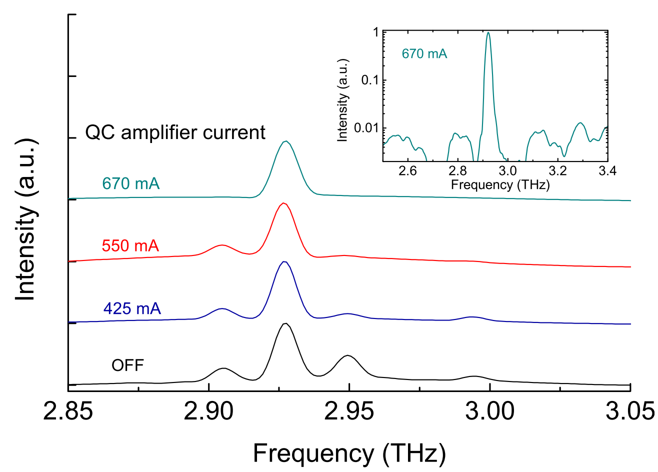

FIG. 4. QC amplifier output emission spectra recorded at 4.5 K at different QC amplifier biases. The driving current for the seeding QCL was kept constant at $1.5 \times J_{th}$, where the driving currents for the QC amplifier were shown in the plot. The inset shows the measured emission spectrum on log scale from the QC amplifier at 670 mA. All the spectra are normalized to the same scale and the frequency resolution is limited by the FTIR resolution of $0.25\,cm^{-1}$.

and the seeding QCL is the same, more enhanced radiation from the main mode also induces more radiation coupled back into the QCL cavity, which in turn reduces the relative mirror losses and then enhances the net gain over this mode from the QCL.

In conclusion, we have developed a terahertz optical amplifier based on a quantum cascade laser structure at 2.9 THz. By depositing an optimal antireflective coating on the QCL facet, the lasing action was fully suppressed and the bare cavity gain was achieved. Pumped by a separate quantum cascade laser, we observed an amplification of ∼30 dB. Furthermore, the amplifier also works as a single mode filter, where a single mode emission was obtained at the roll-off point.

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