Terahertz quantum cascade amplifier

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Abstract— **We have demonstrated a terahertz (THz) optical amplifier based on a 2.9 THz quantum cascade laser (QCL) structure. 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 THz QCL of the same active region design to the QC amplifier. A maximum optical gain as large as 30 dB with single-mode radiation output is demonstrated. Furthermore, a THz imaging system based on the effect of self-mixing in this QC amplifier has also been demonstrated.**

I. Introduction

Quantum cascade lasers[1] (QCLs), based on the principle of light emission driven from electron transitions between individual subbands within the conduction band, have been proven a good candidate of coherent signal source for many applications such as metrology[2], imaging[3], and also high-resolution spectroscopy[4]. 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, and as a result a severly astigmatic beam is generated. The gain-switched amplifier scheme was 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, where the gain clamping effect is avoided. However, this approach would only allow to amplify short pulses. So in principle, the straightforward way to achieve a quantum casade (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 as the material for AR coating on THz QCL structures. In an external cavity tuning configuration, SiO_2 was implemented as a coating layer on the QCL facet, where 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. Moreover, parylene C (poly-monochoro-para-xylene) has also been 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, 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.

II. Materials and methods

According to the Fresnel expression, an antireflective layer is obtained when its refractive index n_{AR}, and thickness d, satisfy the conditions $n_{AR}^2=n_a*n_b$ 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 3.69, 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, has been selected as a suitable 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 as the antireflective layer, which is difficult to achieve in reality. 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%, which 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, 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 and 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. 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 respectively. At the end, the 17 μm coating device showed fully suppressed lasing action, where a 17.7 μm actual coating thickness was measured from a planer GaAs chip coated during the same process run. 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 thickness and the calculated one (15.5 μm) might originate from the fact that the deposition rate varies on the laser facet compared with the planer dummy chip, which at the end results in a thinner coating layer on the facet.

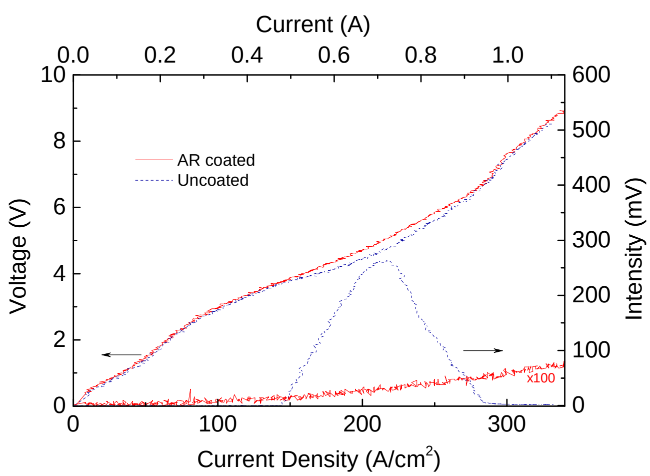

Fig. 1 Voltage and output intensity as a function of the current density for the QC amplifier with (red line) and without (blue dashed line) antireflective coating.

The 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. The voltage and emitted 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 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.

III. Results and Discussion

The QC amplifier was characterized by directly coupling to a separate 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 THz QCL was coupled to the amplifier face to face by mounting them together on the cold plate as shown in Fig. 1, 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. All the measurements were performed in pulsed mode with a 10 kHz repetition rate and a 15% and 20% duty cycle for the 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. 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 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 at the current above 0.45 A for the QC amplifier, where the device exhibited pronounced single-pass amplification behaviour. Above this current, the amplification increased as the bias field became higher. Small drops of the intensity at lower bias current before the amplification were 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, 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 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. Moreover, by plotting the output intensity of the QC amplifier with respect to the input intensity of the 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). This suggestes that the QCL amplifier had not yet been saturated.

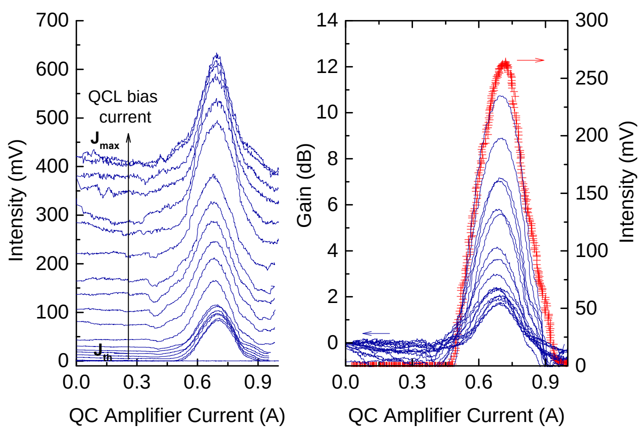

Fig. 2 QC amplifier output intensity as a function of its bias current at different input intensities from the seeding QCL. On the right panel, normalized optical gain of the QC amplifier as a function of its bias current at different input intensities (blue curve), where on the right axis is shown the measured intensity of the QC amplifier without the antireflective coating (red cross).

Furthermore, we also applied the QC amplifier based on the self-mixing effect in a terahertz imaging system. With the optical feedback from the external object to the amplifier cavity, stimulated emission was rebuilt, creating an enhanced voltage perturbation across the device terminal and leading to a prominent self-mixing effect in the QC amplifier. With the QC amplifier serving as both the source and the sensor, a straightforward with high dynamic range imaging system has been achieved.

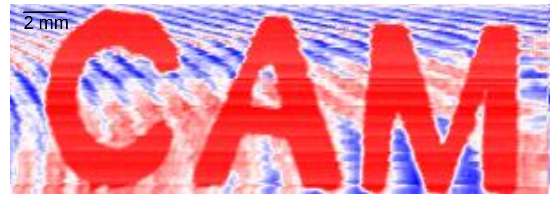

Fig. 3 A high resolution image of a hand writing letters of 'CAM' on the back side of a polyethylene sheet. The pixel size is 100 μm*100 μm.

IV. Conclusions

In conclusion, we have developed a terahertz optical amplifier based on a quantum cascade laser structure at 2.9 THz. Pumped by a separate quantum cascade laser, an optical gain as large as 30 dB has been achieved. Furthermore, this quantum cascade amplifier was also employed as a self-mixing element for the terahertz imaging scheme. Fast data acquisition rate combined with high dynamic range image was obtained.

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