Self-Mixing Imaging using a Terahertz Quantum Cascade Amplifier

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Abstract—**We demonstrate a terahertz imaging system utilizing self-mixing in a 2.9 THz quantum cascade amplifier, through the use of an anti-reflection coated silicon lens to completely suppress lasing action. The fully exploited optical gain of the quantum cascade amplifier allows induced voltage perturbations to be spatially mapped with a signal to noise ratio of up to 55 dB and an acquisition rate of up to 20,000 pixels per second.**

I. INTRODUCTION

THE drive to develop better imaging techniques at terahertz (THz) frequencies holds great promise in advancing a diverse range of fields, including biomedicine, security sensing, quality control and spectroscopic mapping [1]. Established techniques based on time domain spectroscopy (TDS) are capable of investigations over a large bandwidth (~0.5 – 4.0 THz) in both reflection and transmission geometries, but are limited to microwatt output power levels, which restricts applicability.

More recently, a technique has been demonstrated which employs a quantum cascade laser [2] (QCL) to act as a source and detector simultaneously, via the self-mixing (SM) effect [3]. Radiation reflected back from a target is coupled into the laser cavity, which interferes with the intra-cavity field. This in turn produces measureable perturbations in the bias voltage of the device, which contain spatially dependent information about the target. Traditional limitations to this technique at optical frequencies include poor stability under re-injection, and critical sensitivity to feedback strength. In contrast, the THz QCL has proven extremely stable under optical re-injection [4], which has been associated with the high photon to carrier lifetime compared to bipolar lasers, and as such, offers great promise as a source for self-mixing based applications at THz frequencies.

However, a significant limitation exists in the need to operate the device around threshold bias, where the voltage perturbation upon re-injection is traditionally at its largest. This in turn severely restricts the achievable gain, and thus the sensitivity of the system. Therefore, an approach that allows the QCL to operate at the bias point of maximum gain, whilst retaining a prominent voltage perturbation upon re-injection, would have the potential to increase the system signal-to-noise (S/N) manifold.

II. RESULTS

In this work [5], we present a novel approach to SM imaging using a 2.9 THz single plasmon QCL, converted into a quantum cascade amplifier (QCA) [6]. We achieve this via the use of an anti-reflection coated (18.5 μm parylene C) high resistivity hyper-hemispherical silicon lens mounted on the laser facet, which fully suppresses lasing action, and creates an optical amplifier. As an antireflection coating, Parylene C is a polymer with many attractive properties. These include good thermal stability and surface adhesion, low absorption in the THz range, and the ability to be deposited at the required thickness (>10 μm), which proves challenging for alternative materials such as SiO_2. The antireflection coating was applied to a 3 mm diameter lens by vapour deposition under vacuum at room temperature, with a deposition rate of 0.2 – 0.3 μm/min. The coated lens was subsequently attached directly to the facet using a PMMA layer.

The setup was as follows. The Si lens device was mounted in a continuous flow He cryostat, held at a temperature of 4.5 K, and pulsed at 20 kHz, 6% duty cycle. Radiation was collected and focused via a pair of off-axis parabolic mirrors onto a target, which was translated in the plane perpendicular to incidence. The resulting reflections were coupled back into the QCA, and the induced voltage perturbations, resulting from the changes in photon driven transport, were differentially amplified by a factor of 200 with respect to a 20 kHz pulsed reference voltage held at a near equal value to the device bias in the absence of feedback. The amplified voltage signal was then fed to a lock-in amplifier, referenced at the same frequency, for detection.

To characterize the device response in the presence of feedback, two situations were explored; a fully reflecting metallic mirror as the target (maximum optical feedback), and no target (no feedback). The response of the device to these two extremes is shown in Figure 1. The light-current-voltage characteristics with and without feedback (Figure 1. a)) clearly show that the lasing action of the device is suppressed in the absence of re-injection, as a result of the reduction in facet reflectivity, which we estimate to be <5%. With maximum feedback, lasing is restored, due to the re-introduction of the laser field. At the current at which maximum emission is observed (~0.9 A), a significant voltage perturbation of ~150 mV is also visible between the two feedback conditions, which is a result of the change in stimulated photon driven transport through the device. It is this voltage perturbation which we utilise for our imaging system. Figure 1. b) shows the voltage perturbation as a function of device current, obtained from the subtraction of the voltages in both feedback conditions, as measured from an oscilloscope. Additionally, Figure 1. c) shows the perturbation as measured through lock-in detection after differential amplification, showing a S/N at the roll-off point of 55 dB at 6% duty cycle, which is up to 6 times that of reported values of systems operating in continuous wave mode at threshold.

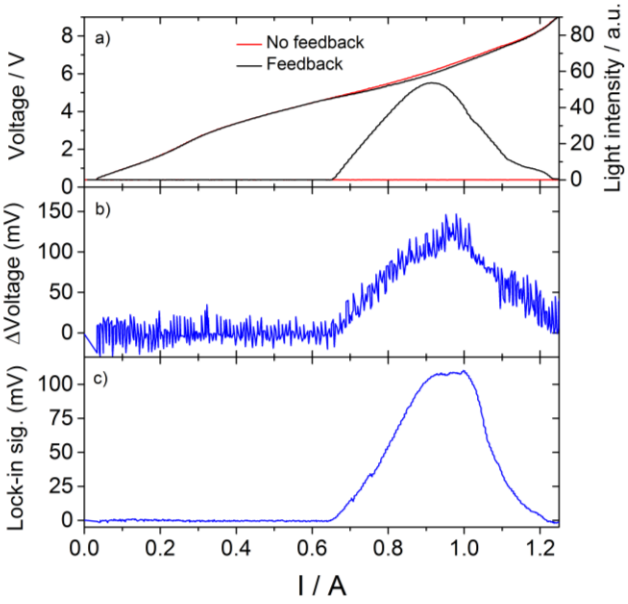

Fig. 1. a) Voltage (left axis) and light (right axis) response as a function of current of the coated Si lens device in the absence of optical feedback (red) and with feedback (black). Without optical feedback, lasing is fully suppressed over the entire dynamic range. b) The voltage difference between feedback and no feedback conditions as a function of device current, obtained by subtracting the oscilloscope voltage responses in a). The prominent voltage perturbation is visible over the entire dynamic range. c) Lock-in signal as a function of device current, obtained by differential amplification with respect to a reference voltage of equal frequency, displaying a clear increase in S/N.

This increase can be attributed to a number of factors. The reduction of the reflectivity of the Si/air interface to <5%, coupled with the focusing action of the lens, act in tandem to significantly increase the amount of radiation coupled back into the cavity, and thus increase the amplitude of measureable signal. Additionally, due to the suppression of lasing, the QCA can be biased at the point of maximum alignment, rather than at threshold, which unlocks the entire gain of the structure.

This increase in signal has the effect of allowing continuous scanning of the target object, which improves the acquisition time compared to discrete step scanning methods, which have been traditionally employed elsewhere, without sacrificing image quality. In order to increase the resolution of the system, a 0.7 mm aperture was introduced into the focal point of the second parabolic mirror. Knife edge tests suggest a resolution of ~300 μm, calculated from the inverse of the spatial frequency at which the modulation transfer function is reduced to 10%. The size of the aperture could in principle be reduced even further, yielding a superior resolution, at the expense of the overall amount of reflected radiation, and thus the system S/N.

An exemplar 18×18 mm, 520,000 pixel image of a coin is shown in Figure. 2 a), taken with an effective pixel size of 25 μm and a lock-in time constant of 10 ms. The roundtrip distance was 600 mm, with a total acquisition time of 3 hours 37 minutes. However, if acquisition speed is of primary importance, only minor image degradation was observed when imaging at a rate of 20,000 pps, and a total acquisition time of ~2 minutes, where a pixel size of 1 μm and a lock-in time constant of 10 μs were used.

Figure. 2. b) shows an 84,000 pixel image of a chrome on glass sample, acquired with a 30 ms pixel time and 10 ms time constant, acquired in 47 minutes. The width of the lines that constitute the letters are 150 μm wide, and here, maximum feedback is shown in white and minimum in blue, corresponding to areas of chrome and glass respectively.

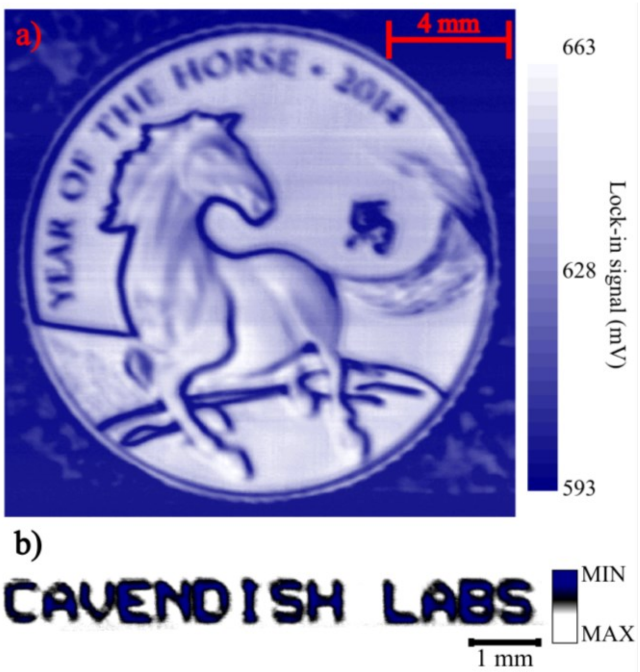

Fig. 2. a) Exemplar single frame image of a gold coin, acquired with a 0.7 mm aperture, 40 pps acquisition rate, with the QCA biased at maximum alignment, and pulsed at 20 kHz, 6% duty cycle. b) Image of a chrome on glass sample, acquired with a pixel size of 25 μm and a 10 ms time constant. The darker areas correspond to lower feedback, due to absorption from the glass substrate.

III. SUMMARY

In conclusion, we have produced a self-mixing imaging system based on a 2.9 THz quantum cascade amplifier. This was achieved through the use of an anti-reflection coated silicon lens attached directly to the laser facet to suppress lasing action, which allowed the full gain of the structure to be exploited. This device was utilised to create a continuous scan, pulsed imaging system, capable of signal to noise ratios of up to 55 dB and acquisition speeds of up to 20,000 pixels per second, which represents significant progress in the field of THz sensing, where potential applicability is extremely far-reaching.

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