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Electrical Modulation Schemes for Imaging by Self-Mixing in Terahertz Quantum Cascade Lasers

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1. Introduction

The use of a single terahertz (THz) quantum cascade laser (QCL) device as both emitter and detector in a self-mixing (SM) scheme allows for the development of fast, sensitive and compact coherent systems for imaging and interferometry. Due to the continuous wave nature of SM experiments, a mechanical chopper is commonly used to enable lock-in detection [1,2]. However, this imposes an upper limit (~200Hz) on the modulation frequency, which is far below the ~10–100 GHz optical feedback response bandwidth of the QCL. We overcome this bottleneck using electrical modulation schemes for two- (2D) and three-dimensional (3D) imaging. Furthermore, by applying a saw-tooth modulation we demonstrate a swept-frequency self-delayed homodyne scheme for coherent 3D imaging without the need for longitudinal displacement of the sample. Using this same scheme we also demonstrate measurement of the current tuning coefficient of the QCL.

2. Methodology and results

The experimental setup employing mechanical modulation has been described elsewhere [3]. In this case the QCL was driven using a DC current just above threshold (I_{th}), where the laser is most sensitive to feedback. The electrical modulation technique described here used a DC driving current just below I_{th}, with a square wave modulation used to drive the QCL above I_{th}, thereby modulating the SM signal. This technique not only reduces the number of optical components but the modulation frequency is no longer mechanically-limited, enabling faster acquisition.

By comparing images taken using mechanical and electrical modulation at 200 Hz we have found comparable image clarity with similar figures of merit K [3] under equivalent measurement conditions. Specifically, with 50 ms integration per pixel, we obtained K = 140 and 155 for mechanical and electrical modulation schemes, respectively. With the electrical modulation frequency increased to 60 kHz a comparable value K = 140 was obtained (see Fig. 1a). For this higher modulation frequency it was also possible to decrease the acquisition time per pixel by a factor of ten, limited only by the acquisition hardware, with only a modest degradation in image quality (K = 95).

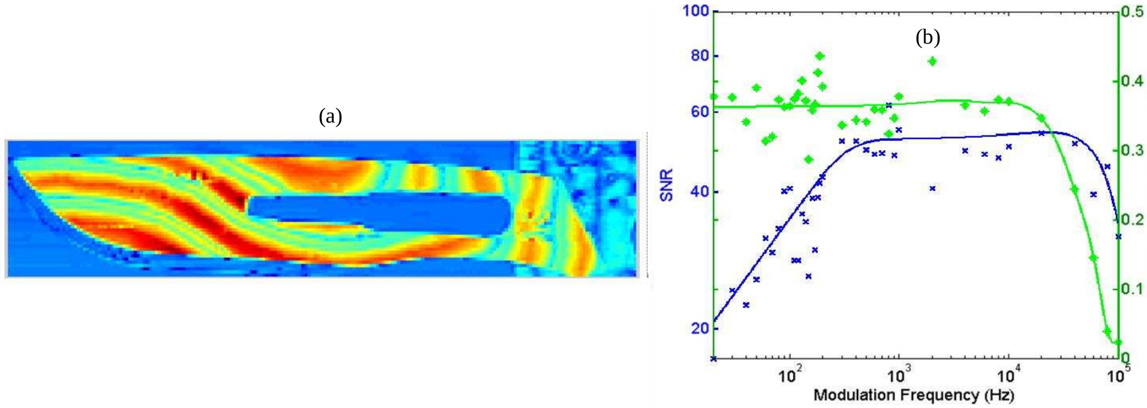

Fig. 1. (a) A scalpel blade imaged using the electrical modulation scheme at 60 kHz with a 50 ms time constant. The discolouration on the right is the mounting point for the scalpel. (b) Using a 5ms time constant, the SNR was measured for varying modulation frequencies. The effect of high frequency modulation can also be observed on the signal power. Raw data is shown with smoothed lines fitted to guide the eye.

To further characterise this modulation scheme we performed a study of the signal-to-noise ratio (SNR) of the SM signal for varying modulation frequencies and lock-in time constants. As shown in Fig. 1b, with increasing modulation frequency an improvement in SNR is observed due to a reduction of 1/f noise. At high frequencies the SNR degrades due to the modulation frequency limit of the laser driver, although we anticipate the modulation frequency could be increased far beyond this range, in principle.

This electrical modulation scheme has also been applied to coherent 3D imaging [4]. In this case the sample was raster-scanned in two dimensions, but also scanned longitudinally at each pixel with the resulting SM waveform being recorded. The phase of the resultant interference pattern was then be extracted by Fourier transform to resolve the sample depth at each pixel. Comparable 3D images and depth profiles have been obtained using both electrical and mechanical modulation techniques (see Fig. 2).

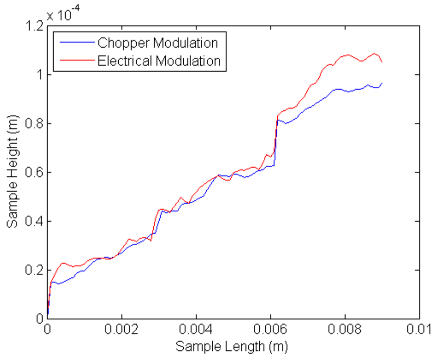

Fig. 2. Depth profile of a GaAs wafer comprising three steps of height 10µm formed by wet chemical etching. The profiles were extracted using electrical (red) and mechanical (blue) modulation techniques showing comparable results.

Finally, we report a swept-frequency self-delayed homodyne scheme through use of saw-tooth electrical modulation, which has the effect of sweeping the laser system through a set of compound cavity resonances. In this manner coherent imaging has been performed without mechanical modulation or longitudinal scanning of the sample, thereby removing these bottlenecks to the acquisition rate of the system. By taking a Fourier transform of the resulting SM signals on a pixel-by-pixel basis, both amplitude-like and phase-like images of samples have been obtained. For this 3D image reconstruction process, the current tuning coefficient of the QCL is required. To this end, we have developed a technique based on mechanically stepping the cavity length and tracking the phase of the SM fringes. By relating these quantities, the tuning coefficient of the QCL can be obtained (see Fig. 3). We obtained a value of -5.4MHz/mA, in agreement with previously published values [5].

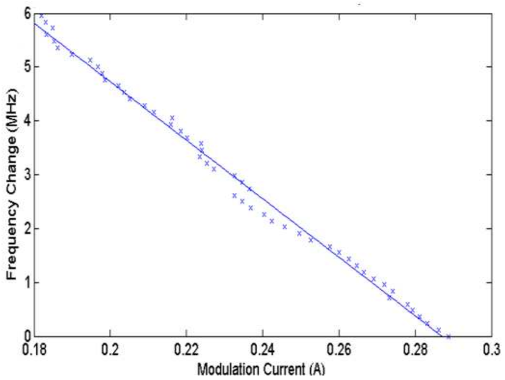

Fig. 3. The current tuning coefficient of the QCL was extracted by mechanically stepping the cavity length and tracking the resultant SM fringes

4. Summary

The operation of electrical modulation techniques for SM imaging and interferometry has been demonstrated resulting in reduced experimental complexity, faster imaging rates and improved noise figures. A swept-frequency self-delayed homodyne scheme has been demonstrated for coherent 3D imaging and measurement of the current tuning coefficient of QCLs.

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