Three-dimensional terahertz imaging using swept frequency feedback interferometry with a quantum cascade laser

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Introduction

Self-Mixing (SM) interferometry using terahertz-frequency quantum cascade lasers (THz QCLs) is a compact and highly-sensitive coherent sensing technique in which optical feedback effects in the laser are used to infer the reflectivity and displacement of a remote object. In this work, we demonstrate coherent 3D THz imaging using a swept-frequency SM scheme. This eliminates the need to scan samples longitudinally [1] to obtain interferometric data, enabling faster acquisition rates (~40 pixels/s) limited only by computational speed. We achieve < 0.1 µm depth resolution for a sampling time of 10 ms/pixel.

Three-dimensional coherent imaging

A 2.65-THz (λ ≈ 113 µm) QCL was driven using a sawtooth current of frequency $f_{mod} = 1$ kHz (90% duty cycle) and amplitude 100 mA superimposed on a 1050-mA dc bias, resulting in an 850-MHz laser-frequency modulation. The radiation from the QCL was focused onto a target object, and reflected back into the laser facet using the approach described in [2]. The sample was raster-scanned in two dimensions orthogonal to the beam axis, and the interferometric fringes in the QCL voltage (resulting from the frequency modulation) were recorded at each position (Fig. 1). At each pixel, the QCL voltage was averaged over N modulation periods. The sampling time per pixel, $t_{\mathrm{samp}} = N/f_{\mathrm{mod}}$, could thus be controlled by the averaging and the modulation frequency. Although acquisition time is limited to ~25 ms/pixel owing to software and hardware limitations in our system, this is significantly faster than the 20 s/pixel reported previously for mechanically modulated systems [1].
The sample comprised a wet etched, GaAs structure [1] consisting of three stepped regions, with the upper half gold-coated to provide regions of differing reflectivity. Fig. 1 shows SM fringes acquired from two sample regions. The different surface height is manifested as a relative phase shift, while the amplitude corresponds to surface reflectivity. 2D maps of depth and reflectivity were thereby obtained from the SM fringes at each position.

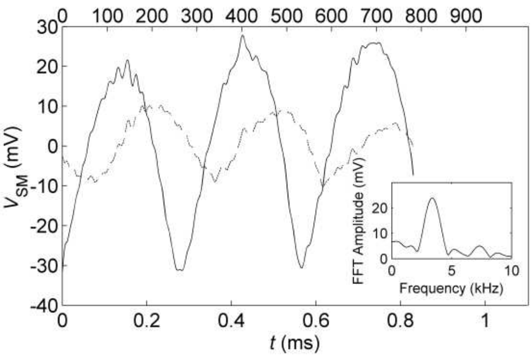

Fig. 1: SM voltage waveforms acquired from two positions on the sample surface. The solid and dashed lines correspond to gold-coated and uncoated regions respectively. Inset: Magnitude of the complex FFT for the solid line.

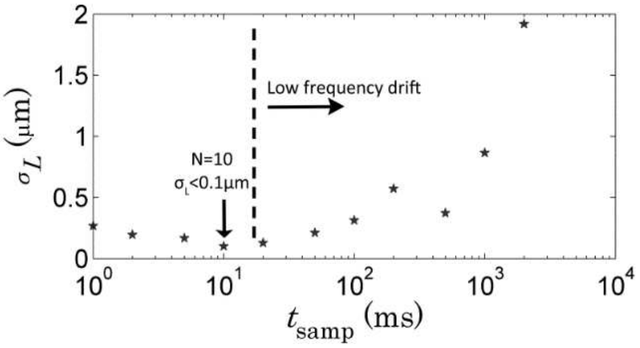

Fig. 2: Depth resolution σ_L determined from the standard deviation of repeated depth measurements, plotted as a function of sampling time per pixel, t_{samp}.

The depth resolution of our system is limited by voltage noise in the SM waveforms (which can be reduced through averaging) and by laser-frequency instability, caused by temperature and current fluctuations. Thermal drift, in particular, can result in frequency drifts of several MHz over a time-scale of seconds [3]. To quantify these effects, 50 SM waveforms were acquired successively and the cavity length determined in each case for various degrees of averaging. The standard deviation σ_L of the measured cavity lengths can be interpreted as the depth resolution as a function of t_{samp}, as shown in Fig. 2. For short sampling times <10 ms, greater averaging results in a reduction of σ_L, with a minimum resolution of <0.1 µm (corresponding to phase change Δφ ~ 0.6°). As sampling time increases beyond this, the low-frequency frequency drift degrades the depth resolution.

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[3] S. Barbieri *et al.* Opt. Lett. 29, 1632-1634 (2004)