Proceedings Paper:

Dean, P, Taimre, T, Lui, A et al. (13 more authors) (2014) Coherent THz imaging using the self-mixing effect in quantum cascade lasers. In: Optical Sensors. Optical Sensors, July 27-31, 2014, Barcelona Spain. Optical Society of America , SeTh4B.3 - SeTh4B.3. ISBN 978-1-55752-820-9

https://doi.org/10.1364/SENSORS.2014.SeTh4B.3

Coherent THz imaging using the self-mixing effect in quantum cascade lasers

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Abstract: We demonstrate that the self-mixing effect in terahertz frequency quantum cascade lasers can be used for three-dimensional coherent imaging; swept-frequency interferometry for imaging and materials analysis; and, high-resolution inverse synthetic aperture radar imaging.
OCIS codes: (110.6795) Terahertz imaging; (140.5965) Semiconductor lasers, quantum cascade

1. Introduction

We present recent advances in the development of coherent terahertz (THz) frequency imaging and sensing systems that exploit the self-mixing (SM) effect in quantum cascade lasers (QCLs). SM occurs when radiation from a laser is partially reflected from an external object and injected back into the laser cavity. The reflected radiation interferes ('mixes') with the intra-cavity field, producing variations in the emitted power and terminal voltage [1]. Thus, by combining the local oscillator, mixer, and the detector all in a single laser, this technique allows the development of simple, self-aligned systems that can sense both the phase and amplitude of the THz field reflected from samples.

We demonstrate the coherent nature of this sensing technique in three distinct imaging modalities: (i) depth-resolved reflection imaging, where the phase-shift induced upon reflection is interpreted in terms of the surface morphology of the sample; (ii) a swept-frequency delayed self-homodyning approach that enables extraction of the complex refractive index of a target under test; and, (iii) an inverse synthetic aperture radar (ISAR) technique for imaging below the diffraction limit.

For each imaging modality, the THz QCL consisted of a GaAs-AlGaAs bound-to-continuum active-region that was processed into a semi-insulating surface-plasmon ridge waveguide. Radiation from the QCL was collimated and focused at normal incidence onto the sample using a second identical reflector. The sample was raster-scanned in two dimensions, and the interferometric SM signal monitored at each pixel via the voltage across the QCL terminals.

2. Depth-resolved THz imaging using a QCL

For depth-resolved imaging, the QCL was operated in continuous-wave, just above the lasing threshold. At each pixel the sample was scanned longitudinally and the SM waveform recorded over several periods [2].

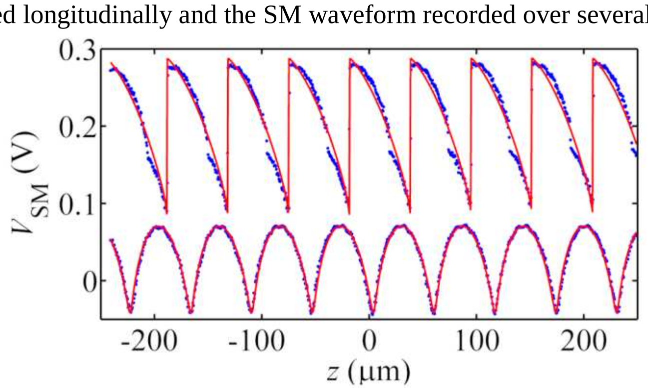

Fig. 1: SM voltage waveforms (blue dots) obtained from two positions on the surface of a stepped GaAs sample, and corresponding fits (red solid lines) to a three-mirror model. The top trace corresponds to a gold-coated region of the sample.

Figure 1 shows typical SM waveforms obtained from two positions on the surface of an exemplar stepped GaAs structure fabricated by wet-chemical etching. The two regions correspond to gold-coated and uncoated regions on different steps, resulting in relative variation in both the phase and amplitude of the waveforms. The phase of the waveforms can be equated to the distance travelled by the THz radiation in the external cavity, and hence to the depth of the surface of the sample, whereas the amplitude can be related to the surface reflectance. Figure 2 shows the resulting three-dimensional profile of the sample and the corresponding reflectance map.

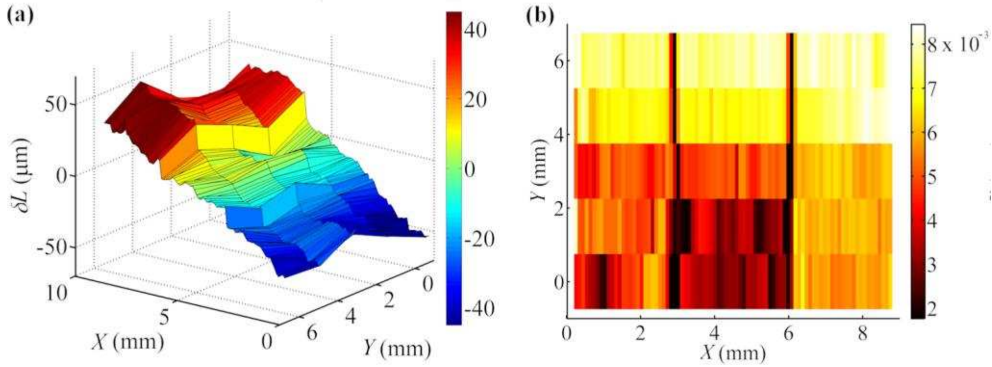

Fig. 2: (a) Three-dimensional reconstruction of a stepped GaAs structure. The colour scale corresponds to the depth of the surface δL. (b) The square of the SM waveform amplitude obtained across the surface of the sample, representing the effective surface reflectance. The top region in (b) corresponds to the gold-coated area of the sample.

3. Swept-frequency interferometry for materials analysis and ISAR imaging

In a second coherent sensing approach [3], a saw-tooth modulation was applied to the laser driving current, which has the effect of sweeping the laser system through a set of compound cavity resonances. In this way coherent imaging is performed without mechanical modulation or longitudinal scanning of the sample. By fitting the resulting SM signal to a three-mirror model, both amplitude-like and phase-like images of the sample were obtained, as illustrated in Fig. 3 for the case of a custom-designed composite target consisting of an aluminium cylinder with three cylindrical bores containing different plastics. The different materials impose different phase-shifts on the incident THz wave according to their complex refractive index. We can thus relate the operating parameters of the laser under feedback to the complex refractive index of the target. Through this approach, following system calibration, we have demonstrated the measurement of complex indices with a high degree of accuracy.

In addition, we have demonstrated an inverse synthetic aperture imaging approach based on this swept-frequency SM scheme [4]. For inverse synthetic aperture imaging, a series of time-domain SM signals were acquired from successive, partially overlapping, THz beam spots on the target. By applying a matched-filter to the SM data we have demonstrated a significant improvement of contrast and spatial resolution in the processed image. We show that this technique enables target features smaller than the spot size to be resolved.

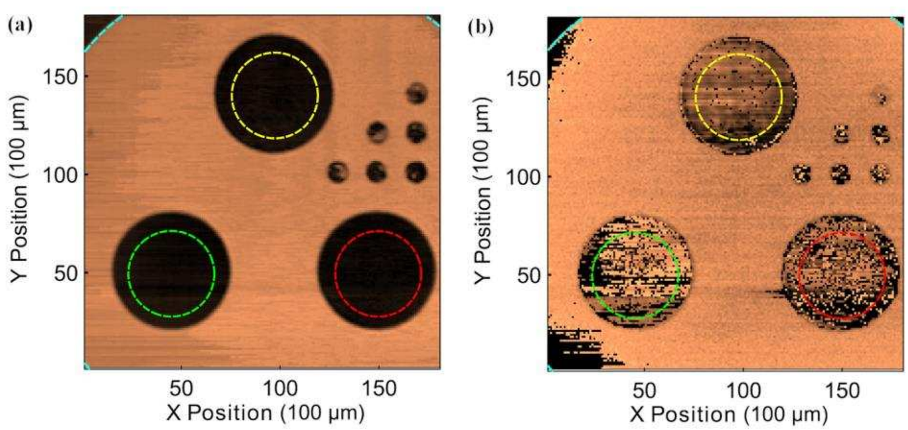

Fig. 3: (a) Amplitude and (b) phase images of an aluminium target containing three bores different plastics.

4. References

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