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Terahertz near-field microscopy using the self-mixing effect in a quantum cascade laser

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***Abstract*—We demonstrate terahertz (THz) apertureless near-field microscopy exploiting the self-mixing effect in a quantum cascade laser (QCL). A THz wave is scattered by a sharp needle positioned above an object and coupled back into the QCL cavity resulting in detection of the THz near-field signal through the self-mixing effect. Using this technique we demonstrate two-dimensional imaging at 2.53 THz with a spatial resolution of 1 µm – the highest image resolution achieved with a THz frequency QCL to date. This method offers an experimentally simple approach to coherent, high-resolution THz imaging.**

I. INTRODUCTION

NEAR-FIELD terahertz (THz) imaging methods enable spatial resolution surpassing the diffraction limit by more than 2 orders of magnitude. Such sub-wavelength resolution has been enabled previously using near-field probes, including sub-wavelength apertures [1], small electro-optic crystals [2] and photo-conductive detectors [3]. A separate type of scattering near-field probe has also been demonstrated to enable the highest spatial resolution, in the sub-100nm range. [4,5]. These probes use a sharp conductive tip to strongly localize the THz field. High spatial resolution thus can be achieved by detecting the wave scattered by the tip. The scattering efficiency typically associated with such a tip apex is, however, extremely small for THz waves. This imposes stringent requirements on THz detectors. As a result, the majority of THz near-field imaging systems have employed the THz time-domain spectroscopy method with a large (>60 dB) detector dynamic range.

THz-frequency quantum cascade lasers (QCL) provide an alternative solution for scattering type near-field microscopy. They serve as a high-power source of THz waves and at the same time can be used as a sensitive detector due to the effect of self-mixing, which has already enabled coherent THz imaging applications [6].

Here we demonstrate THz near-field microscopy exploiting the self-mixing effect in a 2.53 THz QCL. This method offers an experimentally simple approach to coherent, high-resolution THz imaging and we demonstrate the highest image resolution achieved with a THz frequency QCL to date [7].

II. RESULTS

A THz bound-to-continuum QCL was processed into a surface-plasmon ridge waveguide with dimensions 2.4 mm × 50 µm × 10 µm. The device was operated in CW mode (drive current: 945 mA) at 25 K using a continuous flow helium cryostat. Radiation from the laser was focused onto the tip of a horizontally oriented (parallel to the *z*-axis) platinum-iridium needle using a pair of 2-in.-diameter *f*/2 off-axis parabolic reflectors, with the beam axis forming an elevation angle of 50 degrees relative to the needle shaft (see the inset of Fig. 1a). To concentrate the incident THz field, the tip of the 0.5-mm diameter needle was mechanically polished to a radius smaller than 1 µm. A vertically oriented (in the *xy*-plane) sample was mounted on a three-axis computer-controlled translation stage and positioned in proximity to the needle tip at a variable separation *d*.

The QCL radiation scattered from the tip-sample system was coupled back into the QCL facet along the same optical path as the incident beam. The needle tip and the QCL facet therefore form an external cavity of length 40 cm. The scattered light mixes with the QCL intra-cavity field and induces a self-mixing effect, which produces a perturbation to the laser voltage. The amplitude as well as the phase of the scattered field therefore can be monitored through the QCL terminal voltage. [6]

To isolate the signal scattered by the tip apex from that due to the wave scattered by the entire needle, a modulation scheme was employed in which the needle tip was dithered sinusoidally at 90 Hz in the *z*-direction with amplitude of 1 µm, using a piezoelectric transducer. The synchronized in-phase component of the self-mixing signal was then recovered using a lock-in amplifier referenced to the needle modulation.

Enhancement of the self-mixing signal was observed as the sample approached the probe. This allowed us to form scattering-field THz images. An example of two-dimensional mapping of a quartz target patterned with a 2 mm × 5 mm rectangular region of 115 µm-thick gold film is shown in Fig. 1(a).

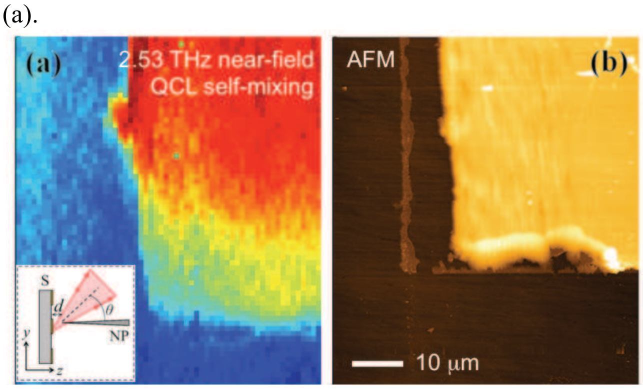

Fig. 1. Two-dimensional THz near-field image of the corner of a rectangular region of 115-nm-thick gold deposited on a quartz substrate. The color scale corresponds to the magnitude of self-mixing voltage observed at the QCL terminals. (b) AFM image of the same region of the sample.

For this measurement the target was positioned close to the needle tip ($d \approx 1$ μm), and the external cavity length finely adjusted to provide the maximum signal on the lock-in amplifier.

Fig. 1(b) shows the same area of the sample containing a corner of the metallic pattern, imaged using a commercial AFM. The corner and even defects of the patterns, which are much smaller than the wavelength, appear in the THz image.

To determine the image resolution the edge response functions (ERFs) along orthogonal directions were extracted by averaging ten adjacent rows of pixels traversing the edge of the gold-coated region along the x and y directions, respectively. From the full width at half maximum of these derivative functions, we determine the spatial resolutions for the x and y directions as $\sigma_x \approx 1$ μm and $\sigma_y \approx 7$ μm, respectively [7].

The value of σ_x is consistent with the estimated tip diameter and represents a resolution ~λ/100. For the y direction, the image of the metallic edge is less clear. We note that the edge oriented perpendicular to the plane if incidence can facilitate excitation of a surface wave [1]. The presence of such surface waves would result in a contribution to the scattered field, which would yield a smoother ERF.

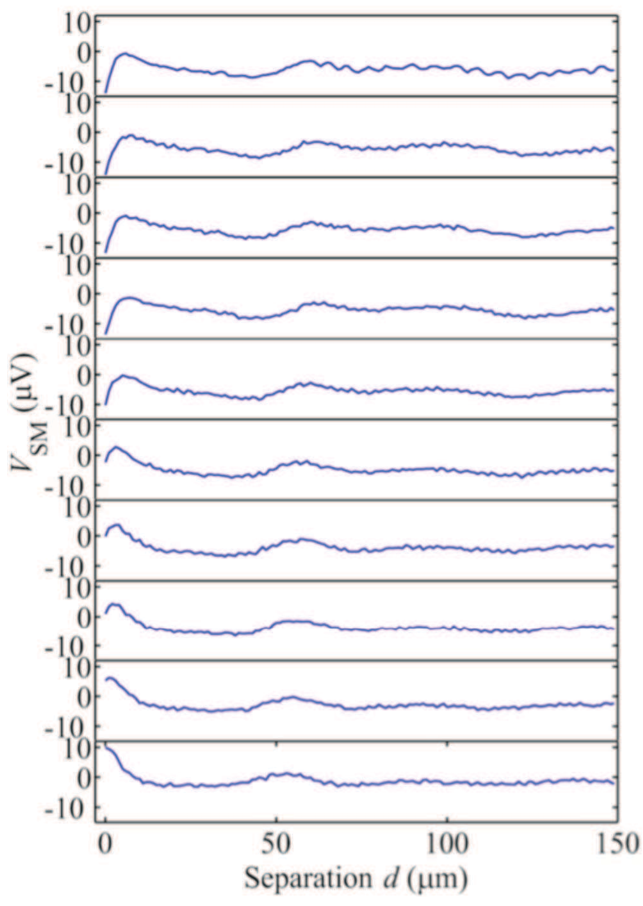

Fig. 2. Self-mixing voltage V_{SM} recorded as a function of tip-sample separation d, for different positions of the needle tip within the beam focus. The tip was held at the same position while the sample position was adjusted to vary the separation d for each curve.

An important consideration in our near-field microscopy implementation, based on self-mixing interferometry, is the effect of the external cavity round-trip phase on the detected signal. To investigate this effect a series of successive approach curves were recorded with the tip stepped incrementally through the incident beam in the z direction; for an increment Δz the round-trip path length in the external cavity formed between the tip and the QCL facet decreases from the nominal value $2L_0$ by an amount $2\Delta z \cos\theta$.

The approach curves shown in Fig. 2 correspond to the needle tip being stepped in the z-direction by an amount varying (bottom to top) from $\Delta z = 0$ μm to $\Delta z = 18$ μm in steps of 2 μm. These measurements show that the detected self-mixing signal depends sensitively on the length of the external cavity formed by the tip of the needle and the laser facet. The self-mixing signal can even change sign in the region $d < 10$ μm, where the enhancement of the field due to the tip is large.

In summary, we have demonstrated THz apertureless near-field imaging using a QCL source and a coherent detection scheme based on self-mixing interferometry. We use sharp metallic needles to obtain two-dimensional THz images of exemplar targets with a spatial resolution down to ~ 1 μm (~λ/100). This represents the highest image resolution achieved with a THz QCL source to date. The self-mixing detection scheme offers an experimentally simple and compact approach to coherent, high-resolution THz imaging. Detailed investigation of the self-mixing signal dependence on the sample-probe separation and the length of the external cavity will be discussed.

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