Near-field microscopy with phase sensitive coherent detection employing quantum cascade lasers

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***Abstract*—We demonstrate a novel architecture for a THz near-field probe, which enables coherent imaging with subwavelength spatial resolution using THz quantum cascade lasers. An InAs nanowire acting as a THz detector based on the field effect transistor concept is integrated inside a subwavelength input aperture of the near-field probe to detect intensity of the THz field and its phase. To determine the phase locally, the THz field is superimposed on the reference THz field incident on the aperture of the probe from the back side. In this configuration, the THz detector exhibits coherent gain and sensitivity to the relative phase between the local and the reference THz fields.**

I. INTRODUCTION

NEAR-FIELD imaging with terahertz (THz) waves have been demonstrated for a range of applications using various types on near-field probes, including probes, which contain subwavelength size input apertures [1], and various types of THz sources. Until recently quantum cascade lasers (QCLs) were rarely employed for THz near-field imaging [2,3]. Among the developed THz sources, QCLs promise to provide high-power and high spectral purity THz radiation, ideal for imaging and high-spectral resolution THz spectroscopy. To enable THz near-field microscopy with QCLs as the THz source, we recently developed an aperture-type near-field probe, and demonstrated detection and sub-wavelength resolution imaging of THz waves [3].

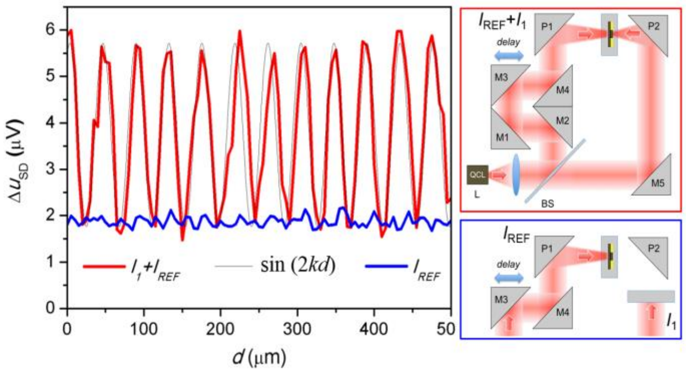

Fig. 1. Schematic diagram of the optical system for THz near-field imaging using the near-field probe with the integrated detector (top right). The detected photo-voltage Δu_{SD} as a function of the reference beam delay when both the illumination and the reference beams are present (*top right*), and for the illumination beam blocked (*bottom right*).

Phase information is essential in near-field imaging [1]. In THz near-field applications employing QCLs, the phase is typically retrieved using an external interferometer or the self-mixing effect [2]. The external phase detection schemes however demand high sensitivity for THz detectors because the fields of prime interest are evanescent, and thus they couple poorly to the external detector.

Here, we demonstrate a THz near-field probe, which enables detection of the phase as well as the wave intensity by using interference of the THz local field with a reference field, inside the near-field probe. To detect the THz field, a nano-scale THz detector based on the field effect transistor (FET) was integrated inside the probe. This architecture paves the way to room-temperature sub-wavelength resolution coherent THz imaging with a compact and versatile system based on QCLs.

II. RESULTS

The phase and intensity of the local THz field was measured interferometrically by combining the field coupled though a subwavelength aperture of the near-field probe with the reference THz wave directed on the back side of the probe. Inside the probe aperture (15 μm), we integrated an InAs nanowire THz detector based on the field effect transistor (FET) concept to detect the local intensity of the THz field and its phase. Asymmetric feeding of THz radiation into the FET enables THz detection, and thus we implemented an asymmetric input aperture shape as described in [3].

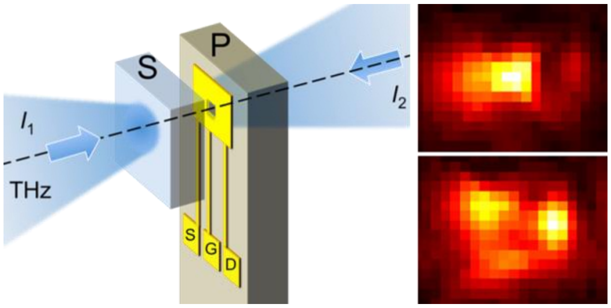

Fig. 2. Illustration of THz near-field imaging arrangement showing a sample (S), the probe (P), and two THz beams incident on the probe aperture. THz images on the right-hand side illustrate "in-phase" (*top*) and "out-of-phase" (*bottom*) interferometric patterns of a focused THz beam. Each image is 150 μm X 200 μm.

A THz beam from a QCL operating at 3.4 THz (average power: ~50 μW; pulsed mode with the duty cycle of 2%) was split by a beam-splitter made of a silicon wafer. The transmitted beam was directed toward the front side of the near-field probe, whereas the reflected beam was first passed through a delay stage, which allowed adjusting the length of the reference beam path, and then directed to the back side of the near-field probe (Fig. 1). Parabolic mirrors (P1 and P2) were used to focus the two beams on the probe aperture.

Each of the two beams, the reference (I_{REF}) and the signal beams (I_1), individually produced the source-drain voltage Δu_{SD} of ~2 μV at the output of the THz nanowire detector. However, when the two beams are present, the source-drain voltage depended on the position of the delay stage, and it varied between ~2 μV and ~6 μV, indicating coherent superposition of the fields from the two beams.

Periodic variation of the source-drain voltage was observed at the output of the FET detector when the relative phase of the reference beam was adjusted (Fig. 1). The average period was 43.5 μm. It corresponds to the QCL wavelength of 87 μm. This periodic variation is a clear signature of interference of the local field with the reference beam.

The constructive interference of the fields from the two beams also results in the source-drain voltage of ~6 μV, which is larger than the sum of the voltages produced by the individual beams (2 μV + 2 μV). We verified that the output voltage of the detector is directly proportional to the THz wave intensity for individual beams [3]. Therefore the fact that the source-drain voltage for the combination of the beams is larger than the sun of the individual components indicates the coherent gain in the detector, and thus a possibility for amplifying weak THz fields coupled into the aperture by using a stronger THz reference wave. The coherent gain can be especially useful for THz near-field microscopy because the THz fields coupled through a deeply sub-wavelength aperture experience very strong attenuation [4,5].

The phase sensitivity can be exploited in THz near-field microscopy as illustrated in Fig. 2. A sample (S) can be placed in front of the near-field probe (P), which is raster scanned to form an image of the THz field.

Here we demonstrate the use of the imaging system for beam profile imaging. The beam from the QCL was focused using the parabolic mirror, and the near-field probe was scanned in the focal plane to obtain the intensity distribution for the beam, which showed Gaussian profiles in the vertical and the horizontal axes.

In the presence of the reference beam however, the simple Gaussian intensity distribution changed into a more complex interference pattern that showed minima and maxima within the beam profile.

Figure 2 shows two examples of the phase sensitive images of the focused beam. For the top image, the phase of the reference beam was adjusted to ensure that intensity maximum is centered within the beam, i.e. the reference and the signal fields are in phase at the beam center. The image shows a profile similar to the profile measured without the reference beam, however an interference pattern can be seen at the edges of the profile. The interference pattern was not present in the image obtained without the reference beam. It suggests that the phase of the field varied within the beam profile.

The bottom image was measured for the reference field being out of phase with the signal field at the beam center. The delay was advanced by ~1/2 of the wavelength compared to the top image. The central peak in this case changed to a minimum, i.e. destructive interference of the fields. The interference pattern in the bottom image is noticeably more pronounced, and it shows two lobes on the left- and right-hand side of the beam. The image shows that the phase of the field within the focal plane varied by more than π, which could have been caused by misalignment of the focusing optics, or by multimode QCL emission.

In Fig. 2, the images indicate that the QCL beam profile within the imaged plane had a varying phase,

III. CONCLUSIONS

We demonstrate phase-sensitive THz near-field imaging using THz aperture-type near-field probes with embedded THz detectors. The monolithic integration of the high-sensitivity room-temperature nanowire THz detector in the probe enables large-area sub-wavelength resolution THz imaging and coherent THz spectroscopy with high power and high spectral purity coherent miniaturized THz QCLs sources. The phase-sensitive images can provide very useful information about the beam quality. The observed coherent gain opens doors for sensitivity improvement in aperture-type THz scanning probe microscopy.

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