Improved Image Quality of Terahertz Transmission Microscope: Example of Graphene Film Observation

Tsutomu Ishi, Takayuki Sudou, Naoki Oda, and Takao Morimoto
Radio Application, Guidance and Electro-Optics Division, NEC Corporation, Fuchu, Tokyo, 183-8501, Japan

***Abstract*—This paper describes non-uniformity reduction in terahertz (THz) imaging system, using a coherent THz source and a THz camera. The beam wobbling technique reduces the interference pattern, but illumination distribution often remains. In order to reduce the illumination distribution, post-image process is applied. In this method, the raw image is divided by the reference image without the sample, which is found effective for improving image quality. The graphene sample is used for validation of this method. The phase shifter is also developed to obtain a high signal-to-noise ratio (SNR) and short image acquisition time in the lock-in imaging.**

I. INTRODUCTION

THz imaging using a real-time THz camera and a high-power THz source is very attractive for non-destructive testing (NDT) application. When a sample is illuminated by a coherent light source such as quantum cascade laser (QCL), the interference pattern is overlapped with image, which degrades image quality. In order to reduce non-uniformity due to the interference pattern, the beam wobbling technique was proposed [1]. In this method, the light beam is wobbled slightly to eliminate bright and dark lines of the interference pattern, using dual-axis galvano mirrors. This newly developed illumination method can dramatically improve image quality, but illumination distribution often remained. This is the issue to be solved, when a spatial distribution of material properties is quantitatively mapped at THz band. In this paper, non-uniformity reduction method is tested to obtain an improved image quality.

Here, the commercial graphene film is used as a sample. Graphene has a potential for use in a number of applications, such as a transparent electrode for touch panel [2]. In recent years, THz imaging of graphene transferred onto high resistivity silicon substrate has been demonstrated, using a THz time-domain spectroscopy (THz-TDS) system [3][4]. Two-dimensional mapping obtained by THz-TDS system consists of the data at a number of measuring points, so that larger area mapping needs more measurement time. THz camera-based system is expected to be applied for such large area mapping, because throughput can be improved.

II. EXPERIMENTAL

Transmission-type THz microscope system with a palm-size THz camera and a compact QCL (LongWave Photonics LLC) was used. Figure 1 shows a schematic diagram of the experiment. THz camera contains a 23.5-µm pitch 320x240 microbolometer focal plane array and operates at 30 Hz frame rate. The QCL is installed in a compact cryogen-free cooler. The lasing frequency is 4.28 THz. The numerical aperture of a microscope lens is 0.5 with magnification of 1.0. In order to compensate the illumination distribution, first, a reference image without the sample was acquired. Then the image with the sample was acquired and divided by the reference image.

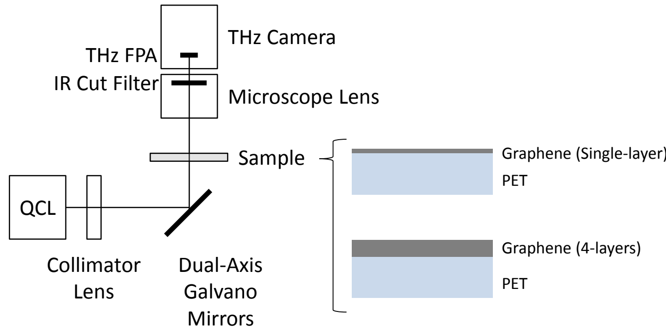

Fig. 1. Schematic diagram of the experimental setup for transmission THz imaging.

Two types of commercial graphene samples were prepared. One was a single layer film transferred on the thin polyethylene terephthalate (PET) sheet. The other was a laminated film of single layer graphene (four layers of graphene film) on the PET sheet. The PET sheet thickness was 0.188 mm.

III. RESULTS AND DISCUSSION

In order to enhance the SNR of the image, lock-in imaging was used. The camera outputs TTL signal that is synchronized to image acquisition. QCL is driven by the synchronization signal from the camera as shown in Fig. 2. Then the QCL-off image is subtracted from the QLC-on image. Figure 3 shows transmission THz images of a single-layer and a 4-layer graphene on the PET sheet. The synchronization frequency f_{sync} was 3.75 Hz, which was one-eighth of the camera frame rate.

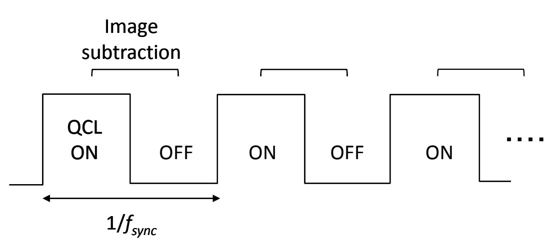

Fig. 2. Explanation of lock-in imaging when QCL is used as THz source.

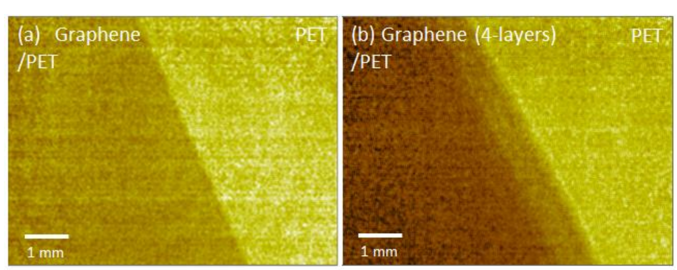

Fig. 3. Transmission THz images of (a) single-layer graphene and (b) 4-layer graphene on the PET sheet after image compensation.

The 16-frames integration and the 3x3 pixel binning (9 pixels were combined into large 1 pixel) were also applied. Previous work shows that the image resolution in THz region is limited by the Fraunhofer diffraction [5]. The pixel binning against the 23.5-μm pitch arrays does not degrade the spatial resolution up to 4x4 at 4.28 THz. The non-uniformity almost disappears in the image. The graphene film is shown in darker color than the PET is, which represents lower transmittance. Figure 4 shows the histograms of the images. Two peaks, which correspond to the regions with and without graphene respectively, are clearly observed for the single-layer graphene sample. On the other hand, another small peak is observed between two main peaks for the 4-layer graphene sample, which suggests an existence of the region with different optical characteristics or edge gradient in the graphene film. In this way, it is possible to evaluate non-uniformity in the film by monitoring the shape of transmittance distribution. This means the beam wobbling technique combined with the post-image process is found effective for improvement in image quality. When the optical response such as transmittance is evaluated with the camera, the linearity of the sensor responsivity has to be taken into account. If the sensor has a nonlinear responsivity in the measuring range, the obtained result should be calibrated.

For the practical use of THz-NDT, high SNR and short image acquisition time is needed at the same time. From the viewpoint, high f_{sync} value is preferable. The lock-in imaging with high frequency, however, causes the SNR decrease because of phase mismatch between the light source operation and the image acquisition in our product. In order to solve the problem, the phase shifter that shifts the phase of the synchronization signal from the camera by one-32nd of the lock-in period was developed. In the case of f_{sync} at 15 Hz, the minimum adjustable time was approximately 2.1 milliseconds. Figure 5 shows the phase dependence of the signal output for 15-Hz lock-in imaging. As the phase shifts, the signal output changes. At the optimized phase, the signal output increases to 1.4 times, compared with the value without the phase shifter. This phase-shift function will be incorporated into the camera in the near future.

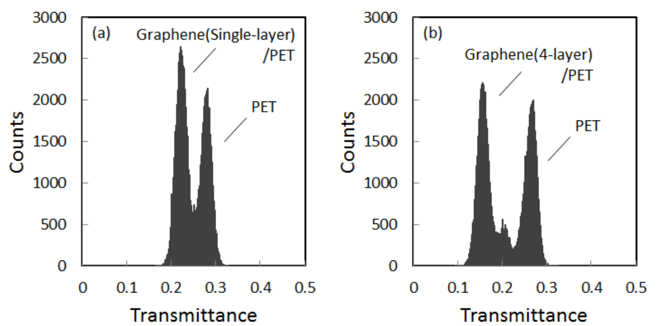

Fig. 4. Histogram of transmittance for (a) single-layer graphene and (b) 4-layer graphene on the PET sheet, obtained at 4.28 THz.

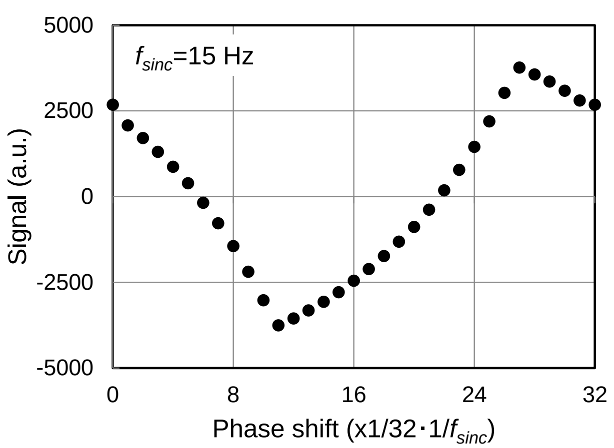

Fig. 5. Phase dependence of camera signal, using the phase shifter at synchronization frequency of 15 Hz.

IV. Summary

Non-uniformity reduction method for THz imaging system has been demonstrated to improve image quality. The method was applied to observation of graphene film and found useful for investigating non-uniformity in the film. The phase shifter has also been developed to obtain high SNR and short image acquisition time in the lock-in imaging.

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