Development of Passive Near-field Spectroscopy for Thermal Evanescent Wave

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***Abstract*—The local dynamics on materials generate thermal evanescent waves that are strongly localized on material surfaces. Sensing the thermal evanescent waves with scattering-type scanning near-field optical microscopy (s-SNOM) without any external light sources enables imaging of the local dynamics at the nanoscale. Here, we report passive THz scanning near-field optical spectroscopy (SNOS), in which a wavelength selective mechanism was constructed on s-SNOM. We have achieved detecting far-field spectrum at wavelengths of 8.0 – 15.5 μm and broadband near-field signals of an Au/SiC sample at room temperature. The spectrum of the thermal evanescent wave enables a detailed analysis of the material surface.**

I. INTRODUCTION

Electromagnetic wave with wavelength of 8 - 20 μm (THz wave) has energy corresponding to local dynamics on materials such as electron motions and lattice vibrations [1]. The local dynamics generate non-uniform charge distribution, generating random electromagnetic waves called thermal evanescent wave which is strongly localized within 100 nm above the material surface. To detect the thermal evanescent wave, we have developed passive THz s-SNOM [2]. Passive s-SNOM does not use any incident light sources. It detects the thermal evanescent wave directly from the sample, whereas active-SNOM is insensitive to it due to the disturbance by the incident lights [3]. Passive THz s-SNOM consists of charge sensitive infrared phototransistor (CSIP) [4], confocal optics, and atomic force microscope (AFM). The spatial resolution is determined by the tip radius. We have achieved the spatial resolution of 20 nm by using a tip with a radius of 20 nm. [5].

However, CSIP is a single wavelength detector (14.5±0.8 μm) and the wavelength of signals detected by passive THz s-SNOM was non-selective, limiting detectable samples and applications. To perform detailed near-field electromagnetic analysis and develop the principles of the passive near-field detection, an extended wavelength range and a wavelength-selective mechanism are strongly required. Therefore, our final goal is to achieve passive near-field spectroscopy and develop the principles of the passive near-field detection mechanism. Here, we report passive THz scanning near-field optical spectroscopy (SNOS) constructed based on grating-type spectroscopy.

II. GRATING-BASED SPECTROSCOPIC SYSTEM

Figure 1(a) is a schematic diagram of the passive THz SNOS. The thermal evanescent wave scattered by an AFM probe is reflected on an Al mirror and is incident on a diffraction grating. Wavelengths are selected by rotating the grating with a piezoelectric rotor, and the rotation angle is measured by a capacitance encoder. The light of the diffraction wavelength is detected by CSIP. To extend the detectable wavelength range, we used three-color CSIP which has achieved the detectable wavelengths of 8.0 – 16.0 μm [6]. Due to the use of three-color CSIP, the wavelength range has been extended to three times larger than that of conventional passive s-SNOM.

The spectroscopic performance largely depends on the grating structure. We selected a blazed grating (shown in Fig.1 (b)) with a rectangular apex due to its high reflectance. It was machined to have 15.5 μm pitch and 17° blazed angle, which were designed to have over 60 % efficiency for the first-order diffraction light and less than 8 % efficiency for the second-order diffraction light at wavelengths of 8.0 – 16.0 μm to avoid mixing of lights of different orders. [7]. The diffraction wavelength and the diffraction efficiency were calculated using Eqs. (1) and (2), where $\theta_i, \phi, \lambda, d, m,$ and β are the incident angle to the grating, the angle between incident and diffraction light, the diffraction wavelength, the grating pitch, the diffraction order, and the blazed angle, respectively [8].

$$m\lambda = d(\sin\theta_i + \sin(\theta_i + \phi)) \tag{1}$$

$$I = sinc^2\left(\frac{\pi d}{\lambda}\frac{\cos\theta_i}{\cos(\theta_i - \beta)} \cdot [\sin(\theta_i - \beta) + \sin(\theta_i + \phi - \beta)]\right) \tag{2}$$

Figure 1(c) shows the calculated diffraction efficiencies (bold and dashed lines are the first- and second-order diffraction efficiencies, respectively) and normalized detected diffraction efficiencies (plotted points) measured by FTIR. Both the measured first and second order diffraction efficiencies were within 5% of the calculated values.

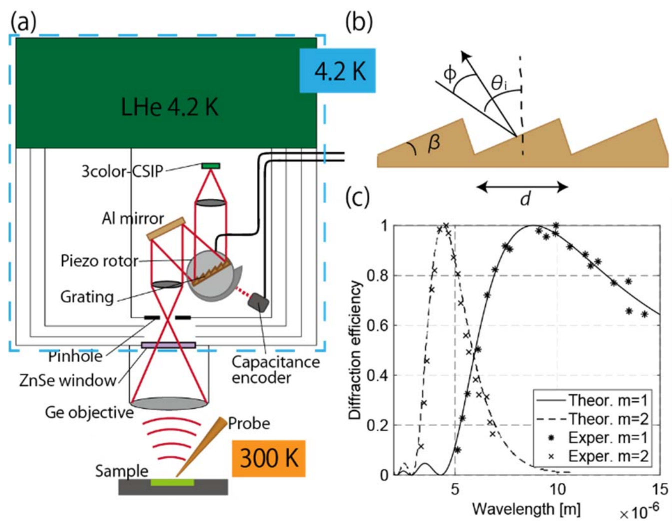

Fig. 1 Grating-based passive THz SNOS (a) A schematic diagram of SNOS. (b) Blazed grating (c) Normalized diffraction efficiency of the grating. Lines are calculated values and plotted points are measured values by FTIR

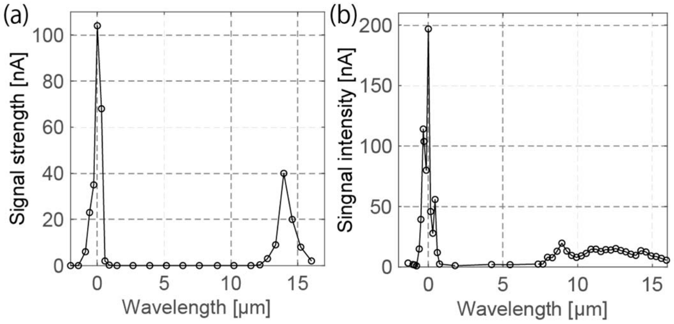

Fig.2 Far-field heat spectrum (a) with conventional one-color CSIP (b) with three-color CSIP

III. Analysis of the Spectroscopic Ability

A. Far-field spectrum of a thermal source

In order to verify the wavelength selective mechanism of SNOS, a thermal source was used to obtain the far-field spectra due to its high stability as an incident THz source. A 500 K heat source was placed at the focal position of the objective lens, and Plank radiation from the thermal source without the AFM probe was detected. Figures 2(a) and (b) show the far-field thermal spectra measured with conventional one-color CSIP and three-color CSIP, respectively. With both conventional one-color CSIP and three-color CSIP, a strong peak at a wavelength of 0 m was obtained. This peak is obtained when the optical path difference between the reflected lights at adjacent apexes is equal to zero (incident angle is 15°, which is called broadband position), meaning light of all wavelengths are incident on the detector. The wavelength resolution is estimated to be approximately 500 nm from the FWHM of the broadband position peak. The rotation angle is calculated from the output voltage of the capacitance encoder. Since the broadband position is fixed to the incident angle of 15°, the rotation angle of the grating is measured relative to the broadband position.

Passive THz SNOS with conventional one-color CSIP and with three-color CSIP detect lights with wavelengths of 13.0 – 15.5 µm and 8.0 – 15.5 µm as shown in Fig. 2(a) and (b), respectively. It indicates that the passive THz SNOS performs the spectroscopic analysis as designed and the detectable wavelength range of SNOS with three-color CSIP is extended to be three times larger than that that with conventional CSIP.

B. Broadband near-field detection of an Au/SiC sample

We passively detected a near-field signal from an Au/SiC sample at room temperature when the rotation angle of the diffraction grating is at the broadband position. An Au/SiC sample shown in Fig. 3(a) is placed at the focal position of the objective lens, and the AFM probe is brought closer to the sample surface by several tens of nanometers and scatters the thermal evanescent wave. The AFM probe oscillates vertically, and a pure near-field signal is obtained using a lock-in amplifier with reference to the AFM probe oscillation [2].

Figure 3(b) is the near-field signals detected by SNOS with conventional one-color CSIP along the arrow in Fig. 3(a). At the wavelength of 13.0 – 15.5 µm (the detectable wavelengths of the SNOS), electron motions on Au generate stronger thermal evanescent wave than that on the SiC substrate. It is

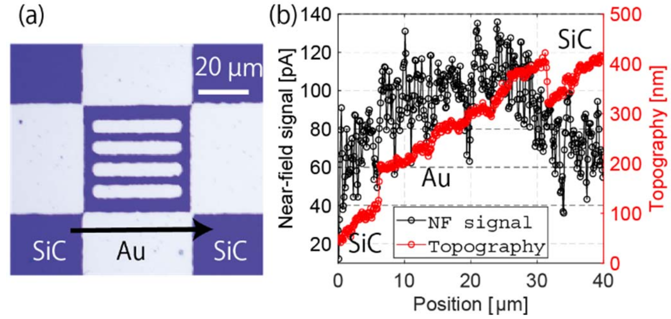

Fig.3 Broadband near-field THz signal on Au/SiC sample. (a) Microscopic image of a micro-pattern Au/SiC sample. (b) Passive near-field signals and topography along the arrow in Fig.3(a).

why the near-field signal on Au is stronger than that on SiC, as shown in Fig. 3(b). Although the spectral intensity obtained by rotating the grating is expected to decrease by more than half, the signal intensity would be slightly higher than the noise level. Therefore, the near-field broadband Au/SiC image indicates that the newly developed passive THz SNOS has a possibility to perform spectroscopic measurements of the ultra-small thermal evanescent waves.

IV. Summary

In this study, we have developed passive THz SNOS based on a grating spectroscopic system. The passive THz SNOS has designed to have a wavelength selective mechanism and the detectable wavelength range was extended by using three-color CSIP. The signal efficiency of over 60 % was achieved with the blazed grating, and the far-field heat spectrum with three-color CSIP indicated that SNOS enables obtaining spectra at wavelengths of 8.0 – 15.5 µm. Furthermore, we have achieved the near-field passive imaging of the Au/SiC sample at the broadband position. The result shows the potential of SNOM to be applied to passive near-field spectroscopy. Although improvements in S/N ratio and signal efficiency are required, it is the first time that the passive THz near-field imaging at room temperature is achieved with the passive spectroscopic optics. Passive THz SNOS would be applied to nano-thermography or nano-chemical microscopy in the near future.

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