Evaluation of detectable angle of mid-infrared slot antennas

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Abstract. For evaluations of a mid-infrared (MIR) detectors with antenna, we constructed an angular dependence measurement system of the antenna properties. The fabricated MIR detector consisted of twin slot antennas and a bolometer. The area of the slot antennas was designed to be $2.6 \times 0.2 \, \mu m^2$ as to resonate at 61 THz, and they were located parallel and separated 1.6 μm each other. The bolometer was fabricated using by a 7.0-nm thick NbN thin film, and located at the center of the twin antennas. We measured polarization angle dependence and directivity, and showed that the MIR antennas have polarization dependence and directivity like radiofrequency antennas.

1. Introduction
Applications using infrared lights are useful for science and engineering technologies. For example, an infrared spectroscopy is important application to analyze any kinds of molecules. An infrared light is emitted from all of materials so that it has been used for a thermography and a night vision camera. They are the reasons why high sensitive mid-infrared (MIR) detectors are required for a security device, a mobility radar, and an astronomy. In particular, explosives such as a triacetone triperoxide (TATP) have strong absorption features in the MIR region. As the TATP is easy to synthesize, it would be very dangerous material so that MIR detectors detecting TATPs are useful for a security system at the airport [1]. Also, a MIR radar will be able to improve resolution of detectors because the MIR wavelength is shorter than millimeter and sub-millimeter wavelength. For example, a millimeter wave (94 GHz) and MIR (28.3 THz) dual band detector has been reported, and each detector play roles in the permeability of smoke and the high resolution, respectively [2]. Thus, MIR detectors are required to have fast and high-sensitive characteristics.

Detectors such as a photomultiplier tube (PMT), a HgCdTe photoconductor (MCT), an InSb photovoltaic detector, and so on, are utilized as the MIR detectors with fast response speed, and their detection principles are based on the particle nature as photon. In general, such detectors usually suffer from a tradeoff between sensitivity and speed because the sensitivity depends on the detection area, and their electrostatic capacitance tends to increase with the area. Thus, it is difficult to realize the MIR detectors with both of fast and high-sensitive characteristics. In order to realize fast detectors without sacrificing detection area, we have proposed to use antennas for detecting MIR waves [3]. It means that the MIR power was collected by using the wave property of MIR instead of particle property. Our group has already reported hot electron bolometer (HEB) mixers with high sensitivity and fast responsiveness in far infrared (FIR) region [4]. Although our objective is to apply the antenna
technology to MIR region, MIR wavelength is several microns so that it is more difficult to fabricate MIR antennas compared with far-infrared antennas. However, recent rapid progress of e-beam lithography technique has made it possible to fabricate extremely small pattern, which means that it can be applied to MIR antenna fabrications. Thus, we have been tried to study HEB mixers [5].

Up to now, studies to apply MIR antennas to detectors has been reported; such as a bolometer coupled with $10 \times 10$ dipole array antenna [6], bowtie antennas [7], square-spiral antennas [8], and so on. In our previous work, we fabricated MIR detectors with nano-slot antenna, and have measured its antenna properties using FTIR [3]. Here, in our experiment, we used the HEB as a detector. Our results indicated that the nano-slot antenna has been properly functioned as the ordinary antenna. Furthermore, we evaluated its response speed of 0.3 ns by the experiment of MIR pulses irradiation with approximately 150 photons per 1 ns [9]. Although we confirmed the antenna function as described above, we haven’t reported the antenna directionality yet. As the antenna’s fundamental property, the measurement of the directionality is requisite. In this paper, we report on the evaluation of detectable angle of MIR twin slot antennas coupled with a superconducting bolometer.

2. Structure and Setup

2.1. Structure of MIR detector

We fabricated MIR detectors, which consist of twin slot antennas and bolometers. Here, we will describe a fabrication process of the MIR detector. A NbN-MgO-NbN (3.5-0.55-7.0 nm) film was evaporated on the MgO substrate and patterned by using e-beam lithography. In order to separate the functions for receiving MIR waves and detecting MIR power, twin slot antennas and a bolometer were fabricated, respectively. The slot antennas were designed $2.6 \times 0.2 \mu m^2$ as to resonate at 61 THz. Here, the frequency of the resonation was calculated using the dielectric constant of a MgO substrate is approximately 2.7 at 61 THz [10]. The slot antennas were located parallel and separated at intervals of 1.6 μm each other (Fig. 1). The bolometers, each of which was fabricated as a 7.0-nm thick NbN thin film (Fig. 2), were located at the center of the twin slot antennas. The bolometer was designed $0.2 \times 0.2 \mu m^2$ which is smaller than a diffraction limit of MIR. The critical temperature ($T_C$) of the NbN bolometer is approximately 13 K so that the detector has to be operated at cryogenic temperature. The antennas and the bolometer were connected using by a coplanar waveguide (CPW). The CPW has 0.2 μm line width and 0.1 μm gap width. In addition, we fabricated a choke filter on the CPW to filter out the MIR waves to electrodes, and the dc bias cuts between both ends of the bolometer.

2.2. Experimental Setup

For evaluating the angle dependence of its sensitivities, we set up directionality evaluation system (Fig. 3). The detector was cooled to 4 K in a Gifford-McMahon (GM) refrigerator, cooling ability of which was 0.1 W. The refrigerator was on a rotatable stage and the detector was mounted at the center of the rotation. MIR laser was introduced through a CaF$_2$ window, which transmitted MIR laser power over 90%. A 4.89-μm quantum cascade laser (QCL) was used as a MIR irradiation source. It was mounted on the X, Y, Z position adjustable stage, and inclined 45° with respect to the X axis. Two polarizers in front of QCL were used. One of the polarizers was positioned near the refrigerator so as to adjust the laser polarization, and another polarizer was used for modulating laser power. For measuring I-V curves, DC source was operated with the $\pm 0.2$ mA range. At first, we measured critical current ($I_C$) of the bolometer and laser power dependence of $I_C$ so as to check the alignment of the laser spot position. Secondly, we measured the $I_C$ and the angle of polarized plane dependence so that we have confirmed whether the detector with antenna detect wave property of MIR. Finally, a directivity of the detector was measured when it mounted horizontal and vertical to X axis (Fig. 4). We measured angle dependences of the detector sensitivity by rotating the refrigerator. We assumed that the directivity would be symmetry because the antenna and bolometer configurations are also symmetry [11]. Thus, we measured antenna radiation pattern from 0° to 80°. We will show the results in next section.
**Figure 1.** SEM image of MIR detector.

**Figure 2.** Cross section of the MIR antenna (Left) and bolometer (Right).

**Figure 3.** Evaluation system of the MIR detector.

**Figure 4.** E-plane and H-plane of the twin slot antenna.
3. Results

Figure 5 shows the I-V characteristics of the NbN bolometer without the laser radiation, and the I_c was observed of 0.135 mA. Although the measurement temperature of the bolometer was not monitored directly, the T_c of the bare NbN film was checked to be 12.6 K by another measurement. Figure 6 shows the MIR laser power dependence of NbN-bolometer’s I_c. Here, the laser was operated at CW mode, and the power was scanned from 0 to 50 mW. We observed the I_c approximately decreased as the laser power was increased, and the I_c was decreased to 0.098 mA at the maximum laser power. The dependence indicated that the laser was properly focused on the bolometer. Here, although the I_c was not decreased monotonous, we guess that the coupling of the MIR antenna and the bolometer changed by laser power.

Next, we observed the polarization dependence of the I_c to confirm the function of the antenna. The laser power was kept at 50 mW by adjusting two polarized filters in front of the CaF_2 window. The result of the polarization dependence was shown in Fig. 7. The angle relationships of the polarization and the antennas were shown in insets of Fig. 7. That is, when the degree of polarization was 0°, the electrical fields of the MIR were parallel to the slot antennas. When the degree of polarization was 90°, the electrical fields of the MIR were vertical to the antennas and the resonance was occurred. We designed the antenna configuration to resonate at 61 THz. The result showed the clear suppression of the I_c at the degree of polarization of 90°. The result indicated that the detection mechanism was not by the nature of the particle, but by the nature of MIR waves, which means the MIR slot antenna was properly functioned as the antenna.

Finally, we measured the angle dependence of the I_c depression ratio \(1 - \frac{I_c}{I_{c_{\text{max}}}}\). The results with the polarization angle 0° and 90° are shown in Fig. 8. The clear angular dependences were observed, and they were very like the dependence of that of a radiofrequency antenna. When the detector was positioned at the parallel to the E-plane, the I_c depression ratio was around 15 % at 0°, which was like a dip characteristic. Each antenna of the twin antennas received signals, and the signals transmitted through the transmission line to the detector. The result showed that the signals from twin antenna were interfered and cancelled. We think that the dip characteristic of the E-plane data in Fig. 8 was attributed to the interference. In the measurement, the CPW and bolometer impedances didn’t appropriately match, so it is expected that the signals didn’t absorbed in the bolometer. To estimate the exact behaviour, the dielectric constant of the MgO substrate must be known accurately. As the dielectric constant of MgO was reported of around 1.65 at the wavelength of 4.89 μm [10], the length of the transmission line was almost coincident with the half wavelength of the waveguide. When we measured the angular dependence at the parallel to the H-plane, we observed the strong directivity, but no dips were observed. It was because the phase of the MIR waves incident on the two antennas are the same regardless of the incident angle. We thought that the signal in the E-plane data in Fig. 8 have unnecessary signal from the reflection of the back side of the MgO substrate. Thus, to remove the reflection of the back side, we set up an absorber, which has 98.6 % absorption ratio at 61 THz, behind the substrate. The result of the angle dependence was shown in Fig. 9. This result was roughly in agreement with the result shown in Fig. 8. Because of the existence of the impedance mismatching between CPW and bolometer, the signal received by one antenna will go through the bolometer and interfere with the signal received at the other antenna. When the incident angle is 0°, if the transmission line is in an ideal state, the signal received by the bolometer will be twice that of a single antenna. However, we observed the dip at 0° and we thought the result is due to impedance mismatching.
**Figure 5.** I-V characteristic of the bolometer without laser radiation

**Figure 6.** Laser power dependence of I_c.

**Figure 7.** Polarization angle dependence of I_c

**Figure 8.** E-plane (Left) and H-plane (Right) antenna pattern of the twin slot antennas
**Figure 9.** E-plane antenna pattern of the twin slot antennas without reflectance

### 4. Conclusion

We constructed the directive evaluation system for the MIR detectors with nano-antenna. We measured characteristics of the MIR detector with twin slot antenna and NbN bolometer. The results showed that the very small MIR antennas have polarization dependence and directivity. Thus, it operated like a radiofrequency antenna. The results enable us to fabricate phased-array antenna by reference to the results and improve its sensitivity. The MIR phased-array antenna will be established the large detection area and high sensitivity by gathering many antennas signal. In the future, we adapt this technique to development both of high-speed and sensitive MIR detector for security system and advanced sensing technique.

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