Mid-Infrared Nano-Antenna Technology

Akira KAWAKAMI, Shingo SAITO, Masaharu HYODO, and Shukichi TANAKA

To improve the response of superconducting mid-infrared detectors, we have evaluated nano antennas. We developed a new fabrication process by using e-beam lithography to realize the nano-structures. Nano-antenna consists of a dipole antenna constructed with aluminum strips, and a niobium nitride (NbN) thin film which acts load resistance is placed in the antenna's center. In an evaluation of spectral transmission characteristics, clear absorption caused by antenna effects was observed at around 1,400 cm^{-1} (f=42 THz). The NbN thin film loads of the photo-detector showed good superconductivity.

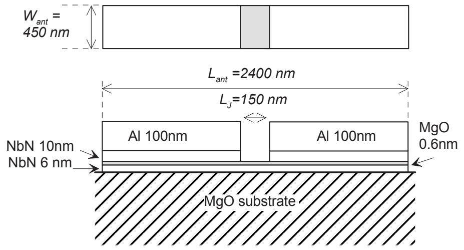
1 Introduction

Electromagnetic waves have the properties of both particles and waves, but many photodetectors are devices with structures and mechanisms based on the assumption that light is particulate. One of the reasons for this is the fact that photons are high in energy with short wavelengths. However, with advances in fine processing technology on nano scales in recent years, new optical devices are being proposed making use of the wave properties of light[1]–[3]. The optical nano-antenna technology that this research aims to advance is an example of this, and it signifies expansion into the field of infrared radiation in radiowave technology, which will enable the establishment of technologies for extremely fine processing below the wavelength of light.

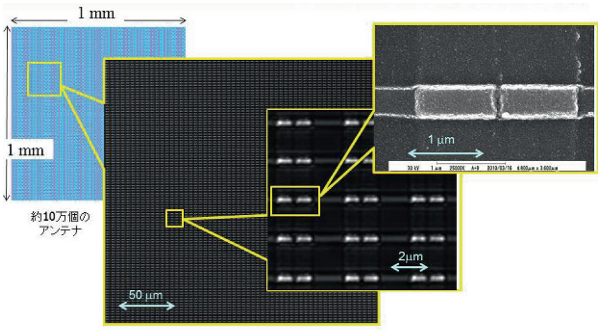
Superconducting near-infrared photodetectors such as the Superconducting Nanowire Single-Photon Detector (SNSPD)[4][5] and the Transition Edge Sensor (TES)[6] are already outperforming traditional solid state detectors in terms of high quantum efficiency, temporal resolution, low dark count rate, etc. However, as with many photodetectors, light is received and detected through the same mechanism, and it is believed that the current structure will hinder dramatic improvement in the speed of response. On the other hand, we had from the past been researching and developing superconducting hot-electron bolometric mixers as ultra-low noise electromagnetic wave receivers in the terahertz frequency range. This mixer consists of a planar antenna for efficiently capturing electromagnetic waves in the air, combined with a microdetector made of a niobium nitride (NbN) thin film strip located at the feeding point of the antenna. This has ensured a wide receiving area and high sensitivity, and enabled fast responses in excess of 2 GHz through impedance matching between the antenna and the thin film superconducting strip that acts as the detector[7]. We therefore recognized the potential for achieving greater speed and efficiency in infrared photodetectors too, by separating the mechanisms for receiving and detecting light as the optical antenna and microdetector, and optimizing their functions. In other words, the objective of this research is to examine the nano-antenna as a new system integrating the optical antenna with the detector. First we will evaluate the properties of the nano-antenna within the mid-infrared light range in order to establish design guidelines and the technologies required in fabrication, and aim to further boost the speed and functionality of infrared photodetectors.

2 Fabrication and evaluation the mid-infrared light nano-antenna

Fabricating an antenna structure in the mid-infrared light range requires the building of fine structures on nano scales. We developed a new fabrication process using electron beam lithography for all lithography processes[8]. Here plasma resistance is insufficient in ordinary resist for electron beam lithography, so a thin film of magnesium oxide (MgO) of 1 to 2 nm thickness was used as the inorganic resist. This thin MgO film was deposited by ion-beam sputtering to avoid damaging the surface of the lower NbN thin films or e-beam resists during sputtering, and allows easy pattern transfer via lift-off process even with electron beam resist. It also has extremely high fluorine



(a) Schematics of a nano-antenna



(b) Micrographs of a nano-antennas

Fig. 1 Schematics and Micrographs of a nano-antennas

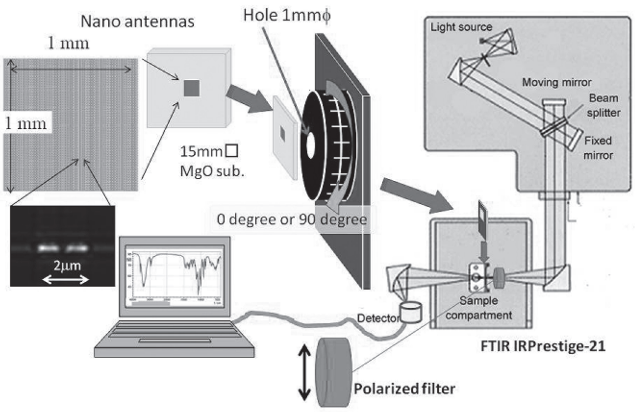


Fig. 2 Measurement setup for evaluation of nano-antenna properties using FTIR system

resistance allowing NbN thin-film (film thickness of several hundred nm) patterning (width of 200 nm) with a MgO film of only a few nm thickness. The electromagnetic field simulator, Sonnet was used to design the nano-antenna. The reported value (n = 1.624@5.35 μm)[9] was used as the refractive index of MgO needed here. When the transmittance characteristics are measured upon connecting a matching load to the nano-antenna, it is observed as an "absorption property" at the frequency of the matching impedance. Furthermore, we thought that the fact that the dipole antenna shows a clear dependence on the plane of polarization would allow us to evaluate and confirm the operation of the antenna in the infrared light range, by

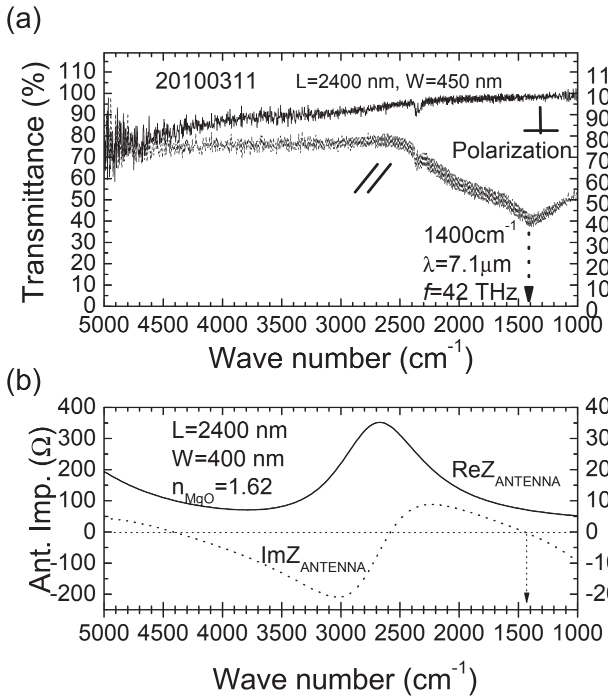


Fig. 3 Wave number dependency of the transmittance of the nano-antenna array(a) and calculated antenna impedance(b).

evaluating its transmission characteristics through mid and near infrared Fourier Transform Infrared Spectroscopy (FTIR).

Figure 1 shows a schematic drawing and photomicrograph of the nano-antenna device. Figure 2 shows the nano-antenna evaluation system using FTIR. The nano-antenna was an Al thin-film dipole antenna, 2,400 nm in length, 450 nm in width, with a thickness of 100 nm. An NbN thin-film strip (load resistance of approximately 60 Ω) of 450 nm width, and a length of approximately 150 nm, with a thickness of 6 nm has been attached to the center of this antenna. To ensure significant absorption properties in this experiment, nano-antennae were positioned at 2.5 μm intervals vertically and 4.5 μm intervals horizontally within the entire 1 mm × 1 mm section at the center of the MgO single-crystal substrate. All transmittance measurements by FTIR were taken at room temperature.

Figure 3 shows the results of transmittance measurements by FTIR and the results of antenna impedance calculations. When the polarization direction of the incident light was in alignment with the antennae, clear absorption properties were observed at the wave number of around 1,400 cm^{-1} (42 THz). On the other hand, when the polarization direction of the incident light was perpendicular to the alignment of the antennae, no obvious absorption properties were observed. It can be seen from the results of calculations on antenna impedance $Z_{ANTENNA}$, that the

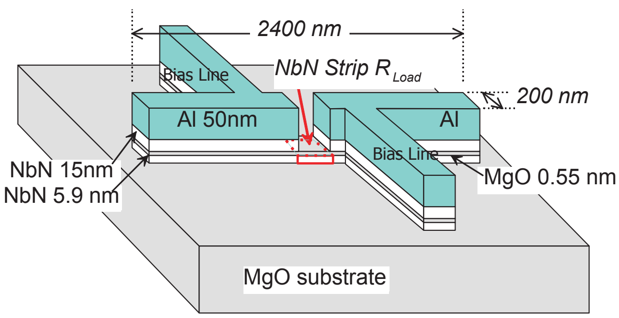


Fig. 4 A Schematic of the detector with a nano-antenna

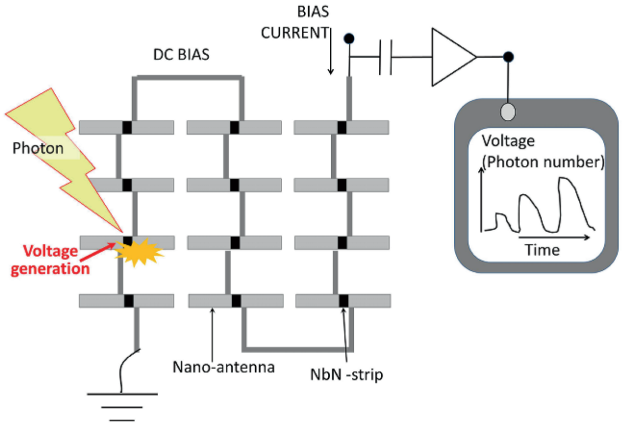


Fig. 5 Schematic of a superconducting photo-detector using nano-antennas

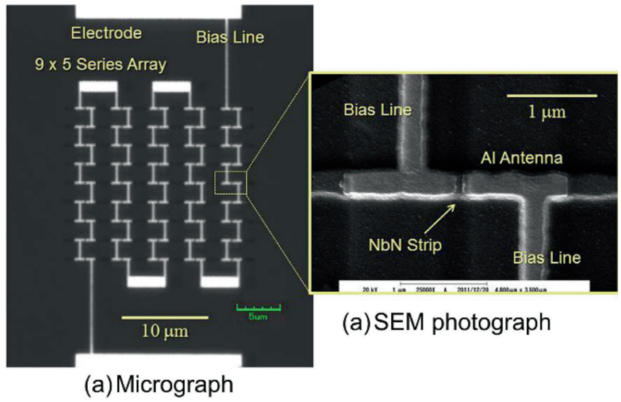


Fig. 6 Photographs of the series array of 45 detectors

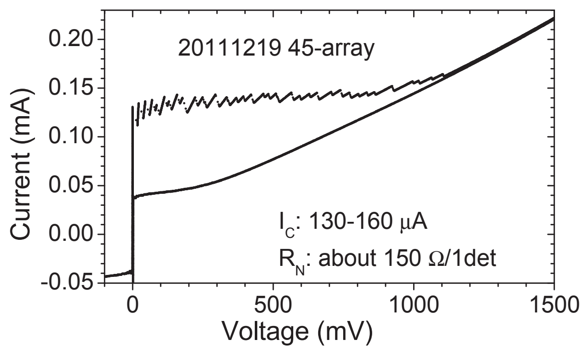


Fig. 7 I-V characteristics of the series array of 45 detectors

imaginary part of $Z_{ANTENNA}$ becomes zero at around this frequency, and the real part becomes consistent with a load resistance of around 60 Ω. In addition, around 50% of the maximum measured absorption rate was virtually consistent with the theoretical absorption rate calculated from the effective area of the antennae and their physical placement intervals, and these observations allow confirmation of the operation of the antennae within the mid-infrared light range.

3 Fabrication of an infrared photodetector with nano-antennae, and evaluation of its fabrication process

This research assumes photodetection from the change in superconductivity due to incident energy concentrated around the feeding point of the antenna, by placing a superconductive thin film strip of a few nm in thickness at the feeding point for the optical nano-antenna. For this assumption to hold true, it is important for the superconductive thin film to retain its excellent superconductivity such as a high superconducting transition temperature or a uniform critical current, even after completion of the nano-antenna. So we trial fabricated a superconductive infrared photodetector with integrated nano-antennae to examine the feasibility of its fabrication process.

The base unit of the trial fabricated a mid-infrared photodetector with integrated nano-antennae as the "detector part" consisting of the nano-antenna and the microscopic superconductive strip at the feeding point of the antenna (Fig. 4). Figure 5 shows a schematic drawing of a serially biased mid-infrared photodetector with integrated nano-antennae. This photodetector consists of multiple detector parts connected in series, to which a bias current that is slightly weaker than the critical current of the microscopic superconductive strip is applied. When a photon enters the antenna, the superconductive critical current at the feeding point is lowered to below the bias current level by the energy of the incident photon. This results in its transition from a superconductive state to a normal conductive state, and we assume the bias current generates a DC voltage. If multiple photons enter the detector, we believe that an output voltage is generated in accordance with the number of superconductive strips in a voltage state.

Figure 6 shows a photomicrograph of the trial fabricated detector with integrated nano-antennae. The antenna length and width are 2,400 nm and 200 nm respectively, and it consists of a detector part with a microscopic NbN superconductive strip (5.9 nm in thickness) of 200 nm in width and length positioned at the feeding point. We positioned 45 detector parts within an area of 20 × 20 μm^2 at 4.4 μm intervals in the direction of antenna polarization, and 2.2 μm intervals in the vertical direction. Figure 7 shows the current-voltage properties of the trial fabricated detector with integrated nano-antennae. 45 spikes were observed corresponding to the number of detector parts connected in series within the 130–160 μA current range. Furthermore, the resistance of a single detector part (NbN superconductive strip load resistance: R_{Load}) was around 150 Ω. The superconducting transition temperature of the superconductive strip was around 11.8 K, but this is an excellent transition temperature for an NbN thin film of 5.9 nm thickness. From this, it was ascertained that its superconductivity had not deteriorated after the fabrication process, and the feasibility of the process was confirmed.

4 Conclusions

We designed and evaluated the properties of the nano-antenna in the mid-infrared range. The antennae we created were dipole antennae, designed on the assumption of operation at 40 THz. As the result of applying an NbN thin film load resistance at the feeding point of the antenna as a matched load, and carrying out transmission spectrum measurements of the nano-antennae, absorption properties were clearly observed at frequencies of around 1,400 cm^{-1} (f = 42 THz) believed to be due to the behavior of the antennae. In our fabrication process, we proposed the use of electron beam lithography in all lithography processes, and created a superconductive photodetector with nano-antennae with the aim of evaluating the fabrication process. The superconductive thin film positioned at the feeding point of the antenna had an excellent superconductive transition temperature (Tc = 11.8 K) and a uniform critical current, confirming the feasibility of the fabrication process. In the future, we plan to evaluate optical response spectra and properties such as speed in optical response in the mid-infrared range.

References

1 L. Tang, S. Kocabas, S. Latif, A. Okyay, D. Sebastien, L. Gagnon, K. Saraswat, and D. Miller, "Nanometre-scale germanium photodetector enhanced by a near-infrared dipole antenna," Nature Photon., Vol. 2, pp. 2262–229, 2008.

2 T. H. Taminiau, F. D. Stefani, F. B. Segerink, and N. F. Van Hulst, "Optical antennas direct single-molecule emission," Nature Photon., Vol. 2, pp. 234–237, 2008.

3 T. Kosako, Y. Kadoya, and H. F. Hofmann, "Directional control of light by a nano-optical Yagi-Uda antennd," Nature Photon., Advanced online publication, 2010.

4 G. Gol' tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, "Picosecond superconducting single-photon optical detector," Appl. Phys. Lett., Vol. 79, pp. 705–707, 2001.

5 S. Miki, T. Yamashita, M. Fujiwara, M. Sasaki, and Z. Wang, "Multichannel SNSPD system with high detection efficiency at telecommunication wavelength," Opt. Lett., Vol. 35, pp. 2133–2135,2010.

6 D. Fukuda, G. Fujii, A. Yoshizawa, and H. Tsuchida, "High Speed Photon Number Resolving Detector with Titanium Transition Edge Sensor," J. Low temp Phys, Vol. 151, pp. 100–105, 2008.

7 S. Miki, Y. Uzawa, A.Kawakami, and Z.Wang, "IF bandwidth and noise temperature measurements of NbN HEB mixers on MgO substrates," IEEE Trans. Appl. Supercond., Vol. 11, pp. 175–178, Mar. 2001.

8 A. Kawakami, S. Saito, and M. Hyodo, "Fabrication of Nano-Antennas for Superconducting Infrared Detectors," IEEE Trans. Appl. Supercond., Vol.21, pp. 632–635, 2011.

9 R. E. Stephens and I. H. Malitson, "Index of refraction of magnesium oxide," J. Res. Nat. Bur. Stand, Vol. 49, pp. 249–252, Oct. 1952.

Akira KAWAKAMI, Dr. Eng.

Senior Researcher, Nano ICT Laboratory, Advanced ICT Research Institute/
Senior Researcher, Collaborative Research Laboratory of Terahertz Technology, Terahertz Technology Research Center
Superconducting Electronics, Nanotechnology Device
kawakami@nict.go.jp

Shingo SAITOI, Dr. Sci.

Senior Researcher, Terahertz and Millimeter wave ICT Laboratory, Advanced ICT Research Institute
THz Wave, Solid State Spectroscopy, Ultrafast Phenomena
sshingo@nict.go.jp

Masaharu HYODO, Dr. Eng.

Senior Researcher, Collaborative Research Laboratory of Terahertz Technology, Terahertz Technology Research Center/
Research Promotion Expert, Plannning Office, Advanced ICT Research Institute
Optoelectronics, Atom Optics
hyodo@nict.go.jp

Shukichi TANAKA, Dr. Sci.

Research Maneger, Nano ICT Laboratory, Advanced ICT Research Institute/
Senior Researcher, Collaborative Research Laboratory of Terahertz Technology, Terahertz Technology Research Center
Physical Properties of Nano Materials Scanning Probe Microscope/Spectroscopy, Condensed Matter Physics, Nano Scale Structure Science
tanakas@nict.go.jp