Receiving Properties of Thin-Film Slot Antenna Arrays for 28-THz-CO₂ Laser Radiation

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Keywords : thin film antenna, slot antenna, antenna array, far infrared

Antenna coupled devices are known to be effective as detectors and mixers in the submillimeter wave and infrared regions. In the present study, a parasitic slot antenna array coupled with a bismuth (Bi) microbolometer was fabricated, and the receiving properties such as antenna patterns and power gain were measured for 28-THz-CO₂ laser radiation.

The single-slot antenna, and the 3-, 5-, and 7-parasitic slot antenna arrays were fabricated on Zinc sulfide (ZnS) dielectric substrates. The length and width of the slot antennas were set to be $0.72 \lambda_0$ ($7.6 \mu\text{m}$) and $0.08 \lambda_0$ ($0.9 \mu\text{m}$) according to an analogy of the experimental results at 2.5 THz, where λ_0 is the free space wavelength. The distance between the slots was $0.5 \lambda_d$ ($2.4 \mu\text{m}$), where λ_d is the dielectric wavelength in the ZnS substrate.

When the CO₂ laser beam was irradiated on the antennas from the air-side, the E-plane antenna patterns of the parasitic slot antenna arrays became increasing sharper as the number of slots in the array increased from 1 to 7. On the other hand, the H-plane antenna patterns did not change with the number of slots because the slot antennas were not arrayed in the H-plane. These experimental results indicate that the antenna theory based on the transmission line model was applicable and that the slot antenna operated in the free space wavelength λ_0 at 28 THz.

Figure 1 shows the E-plane antenna patterns of the single-slot

Fig. 1. E-plane antenna patterns of the single-slot antenna for 28-THz-CO₂ laser irradiation through the substrate

Fig. 2. The dependency of the relative power gain of parasitic slot antenna arrays on the number of slots at 28 THz

antenna when the CO₂ laser beam was irradiated to the antenna through the substrate. The solid circles and the solid curves show the experimental and theoretical E-plane patterns, respectively. In the calculation, we used the multiple reflection model. In this figure, a rippled antenna pattern was observed due to multiple reflection in the substrate because the thickness of the substrate was much longer than the dielectric wavelength of the CO₂ laser. The experimental values agree well with the detailed theoretical pattern. This experimental result revealed that the antenna receiving properties were affected by a dielectric constant, an absorption coefficient and the thickness of the substrate at 28 THz. The E-plane antenna pattern of the 7-parasitic slot antenna array also becomes sharper than that of the single-slot antenna as a result of the array for the irradiation through the substrate.

Figure 2 shows the dependency of the relative power gain of the parasitic slot antenna array on the number of slots for 28-THz-CO₂ laser radiation. In this figure, the open and solid circles show the experimental data, and the broken and solid curves show the theoretical values, respectively. The power gain increased with the number of slots, as expected from the theory, and the power gain for the laser irradiation through the substrate improved by approximately 7 dB compared to the gain for the irradiation from the air-side. Furthermore, the power gain of the 7-parasitic slot antenna array improved by approximately 7 dB compared to the single-slot antenna for the laser irradiation both from the air-side and through the substrate.

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The receiving properties of fabricated parasitic slot antenna arrays on ZnS dielectric substrates for 28-THz-CO₂ laser radiation were investigated. When the CO₂ laser beam was irradiated on the antennas directly (from the air-side), the E-plane antenna patterns of the parasitic slot antenna arrays became increasing sharper as the number of slots in the array increased from 1 to 7. On the other hand, the H-plane antenna patterns did not change with the number of slots because the slot antennas were not arrayed in the H-plane. It was found that the antenna theory based on the transmission line model was applicable at 28 THz. When the CO₂ laser beam was irradiated through the substrate (from the substrate-side), rippled antenna patterns were observed due to multiple reflection in the substrate because the thickness of the substrate was much longer than the dielectric wavelength of the CO₂ laser. It was also found that the antenna receiving properties were affected by the thickness of the substrate. Furthermore, as expected from the theory, the power gain of the 7-parasitic slot antenna array improved by approximately 7 dB compared to that of the single-slot antenna at 28 THz.

Keywords : thin film antenna, slot antenna, antenna array, far infrared

1. Introduction

Infrared rays, which have a wide frequency range, have applications in various fields, including industry, medicine, weather, and astronomy. Infrared sensing techniques are one of the most commonly used applications in these fields, and infrared detector development is active. Quantum and thermal detectors have been used to detect infrared radiation. Although quantum detectors have excellent characteristics in the wavelength region shorter than 10 μm , a coolant system, for example using liquid helium, is required for the longer wavelength region. On the other hand, a bolometer, which is a thermal detector, has several advantages, such as room-temperature operation, a simple structure and constant sensitivity at a wide frequency region. However, an absorbing material is required to absorb the radiated infrared rays⁽¹⁾⁻⁽³⁾, and there are problems such as slow response speed and low sensitivity compared to quantum detectors. One device that has been proposed as a solution to these problems is the antenna coupled device⁽⁴⁾.

Antenna coupled devices, such as MOM diodes⁽⁵⁾, Schottky diodes⁽⁶⁾ and Warm carrier devices⁽⁷⁾, are known to be effective as detectors and mixers in the submillimeter wave and infrared regions. These antenna coupled devices have been mostly used in the form of three-dimensional point contact configuration, and have been utilized in direct detection, harmonic generation, and mixing experiments⁽⁸⁾⁻⁽¹⁰⁾. It is generally thought that the useful properties of these devices arise from nonlinear current-voltage characteristics which persist up to infrared, together with the ability of the metal whisker to function as a receiving antenna,

converting laser radiation to an optical-frequency voltage across the device.

Unfortunately, the extreme mechanical instability of these devices made them impractical, except for the special applications, and encouraged the fabrication of stable integrated devices with recently developed microfabrication techniques.

In order to obtain high sensitive thin-film antenna coupled devices, it is necessary to fabricate a thin-film antenna which can receive the submillimeter wave and infrared radiation efficiently, as well as the detector which maintains its current-voltage characteristics up to the frequencies of the signals received by the antenna.

The authors have been studying a slot antenna and its arrays in the millimeter and submillimeter wave regions⁽¹¹⁾⁻⁽¹³⁾. To date, they have fabricated single slot antennas and their arrays for 4.5 GHz, 94 GHz, 700 GHz and 2.5 THz radiation, and have obtained the results that the fabricated slot antenna and its arrays worked as expected from the theory based on the transmission line model⁽¹⁴⁾ up to 2.5 THz, though the operating wavelength of the antenna had to be changed from the mean wavelength to the free space wavelength at 2.5 THz. The fabricated two-dimensional 8 $\times$ 3 slot-antenna arrays had the power gain of 13 dBi and 8 dBi at 700 GHz and 2.5 THz, respectively.

In the present study, a single slot antenna and parasitic slot antenna arrays were fabricated using microfabrication techniques, and the receiving properties such as antenna patterns and power gain were measured at 28 THz to investigate the applicability of the antenna theory based on the transmission line model at 28 THz, the influence of the substrate thickness on the antenna properties, and the enhancement of the antenna gain as a result of the array.

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2. Antenna Structure and Experimental Setup

Figure 1 shows the SEM photograph of the fabricated single-slot antenna and parasitic slot antenna arrays for 28 THz radiation. Figures 1 (a)-(d) show the photographs of the single-slot antenna, and the 3-, 5-, and 7-parasitic slot antenna arrays, respectively. The antennas were fabricated on dielectric substrates. Zinc sulfide (ZnS), which has a small absorption coefficient of $\alpha = 0.2/\text{cm}^{-1}$ and dielectric constant of $\epsilon_d = 4.77$ at 28 THz, was used as the dielectric substrate. The length and width of the slot antennas were set to be $0.72 \lambda_0$ ($7.6 \mu\text{m}$) and $0.08 \lambda_0$ ($0.9 \mu\text{m}$) according to an analogy of the experimental results at 2.5 THz, where λ_0 is the free space wavelength⁽¹⁵⁾. The distance between the slots was $0.5 \lambda_d$ ($2.4 \mu\text{m}$), where λ_d is the dielectric wavelength in the ZnS substrate⁽¹⁶⁾. A bismuth (Bi) microbolometer was used as the detector and was placed at the center of the main slot antenna. The width of the bolometer was design to be $0.055 \lambda_0$ ($0.6 \mu\text{m}$) in order to obtain the antenna resistance of 50Ω . The DC cuts are slit lines for applying DC bias current to the bolometer. The cuts were inserted at the location that is one-quarter length of the slot antenna. The widths of the DC cuts need to be less than $\lambda_0/100$ ($0.1 \mu\text{m}$)⁽¹²⁾.

Figure 2 shows a schematic diagram of the experimental arrangement. The fabricated antennas were placed on a rotating

Fig. 1. SEM photograph of the fabricated single-slot antenna and parasitic slot antenna arrays for 28THz radiation

Fig. 2. Schematic diagram of measurement system

stage. The 28-THz- CO_2 laser beam was mechanically chopped at 1 kHz and was irradiated to the antennas. When laser beam was irradiated directly to the antenna as shown in Fig. 2, we call the laser beam was irradiated from the air-side. The laser beam was also irradiated to the antenna through the substrate (from the substrate-side) in order to investigate the effect of the substrate thickness to the receiving properties. The Bi microbolometer was biased with a DC current source, and the detected voltage was measured by a lock-in amplifier while changing the angle of the incidence.

3. Receiving Properties of Fabricated Slot Antenna Arrays at 28 THz

The receiving properties of the fabricated antennas were evaluated at 28 THz. Figure 3 shows the receiving antenna patterns of the single-slot antenna and parasitic slot antenna arrays when the CO_2 laser beam was irradiated directly on the antennas from the air-side. Figures 3 (a)-(d) show the patterns of the single-slot antenna, and the 3-, 5-, and 7-parasitic slot antenna arrays, respectively. In these figures, the solid circles and the solid curves denote the experimental and theoretical E-plane patterns, and the open circles and the broken curves denote the experimental and theoretical H-plane patterns, respectively. As can be seen from the figures, the E-plane antenna patterns of the parasitic slot antenna arrays become increasing sharper as the number of slots in the array increased from 1 to 7. On the other hand, the H-plane patterns of the 3-, 5-, and 7-parasitic slot antenna arrays coincide with the pattern of the single-slot antenna because the slot antennas are not arrayed in the H-plane. The experimental values agree well with the theoretical patterns based on the transmission line model. These experimental results indicate that the antenna theory based on the transmission line model was applicable and that the slot antenna operated in the free space wavelength λ_0 at 28 THz.

Figure 4 shows the E-plane antenna patterns of the single-slot antenna and the parasitic slot antenna array when the CO_2 laser beam was irradiated to the antenna through the substrate. Figures 4 (a-1) and (b) show the patterns of the single-slot antenna and 7-parasitic slot antenna array, respectively, and Fig. 4 (a-2) shows an enlarged view of the pattern of Fig. 4 (a-1) at the angles of $\pm 15^\circ$. In these figures, the solid circles and the solid curves show the experimental and theoretical E-plane patterns, respectively. In the calculation, we used the multiple reflection model⁽¹⁷⁾, which is affected by a dielectric constant (ϵ), an absorption coefficient (α) and the thickness of the substrate (h) at 28 THz. From the theory of the transmission line model, the antenna pattern is affected by the thickness of the substrate⁽¹⁴⁾. Especially, because the thickness of the substrate is much longer than the dielectric wavelength at 28 THz, a small difference of the thickness strongly affects the antenna pattern. By carefully choosing the fitting parameter of h to be $189.65 \lambda_d$ in Figs. 4 (a-1) and (a-2) and $189.375 \lambda_d$ in Fig. 4 (b), the experimental values were fitted to the theoretical antenna patterns. All of the theoretical patterns have rippled patterns due to the multiple reflection in the substrate because the thickness of the substrate was much longer than the dielectric wavelength of the CO_2 laser. As shown in Fig. 4 (a-2), the experimental values agree well with the detailed theoretical patterns. These experimental results revealed that the antenna receiving properties were affected by a dielectric constant, an absorption coefficient and the thickness of the substrate at 28 THz.

(a) Single-slot antenna

(b) 3-slot antenna array

(c) 5-slot antenna array

(d) 7-slot antenna array

Fig. 3. Antenna patterns of the single-slot antenna and parasitic slot antenna arrays for 28-THz-CO₂ laser irradiation from the air-side

(a-1) Single-slot antenna

(a-2) Single-slot antenna

(b) 7-slot antenna array

Fig. 4. E-plane antenna patterns of the single-slot antenna and parasitic slot antenna array for 28-THz-CO₂ laser irradiation through the substrate

Furthermore, the E-plane antenna pattern of the 7-parasitic slot antenna array becomes sharper than that of the single-slot antenna as a result of the array and the E-plane antenna patterns shown in Fig. 3.

The H-plane antenna patterns of the single-slot antenna and parasitic slot antenna array are shown in Fig. 5 when the CO₂ laser beam was irradiated through the substrate. Figures 5 (a) and (b) show the patterns of the single-slot antenna and 7-parasitic slot antenna array, respectively. In these figures, the solid circles and the solid curves indicate the experimental and theoretical H-plane patterns, respectively. In these cases, the antenna patterns also

Fig. 5. H-plane antenna patterns of the single-slot antenna and parasitic slot antenna array for 28-THz-CO₂ laser irradiation through the substrate

have rippled patterns due to the multiple reflection in the substrate, as well as the E-plane antenna patterns, as shown in Fig. 5. However, the H-plane antenna pattern of the 7-parasitic slot antenna array coincides with that of the single-slot antenna, as well as the H-plane patterns, as shown in Fig. 3.

Finally, the dependency of the relative power gain of parasitic slot antenna arrays on the number of slots was investigated using the obtained gain of the antenna patterns in the direction of 0° shown in Figs. 3–5. However, the gain of the antenna patterns in the direction of 0° does not take a maximum when the CO₂ laser beam was irradiated through the substrate, as shown in Figs. 4 and 5. The power gain of the slot antenna fabricated on the dielectric substrate takes a maximum when the thickness of the substrate is an odd multiple of $\lambda_d/4$ (14). This is considered to be the result that the thickness of the ZnS substrate is not an odd multiple of $\lambda_d/4$. It is difficult to control the thickness of the ZnS substrate precisely because the thickness of the substrate is much longer than the dielectric wavelength of the CO₂ laser. Therefore, we corrected the gain of the antenna patterns shown in Figs. 3–5 assuming that $h = 189.75\lambda_d$ (the thickness of the substrate is an odd multiple of $\lambda_d/4$) in order to accurately compare the gain of each slot antenna arrays. Figure 6 shows the dependency of the relative power gain of the parasitic slot antenna array on the number of slots for 28-THz-CO₂ laser radiation. In this figure, the open circles and the broken curve show the experimental data and theoretical values, respectively, for the laser irradiation from the air-side. While, the solid circles and the solid curve show the experimental data and theoretical values, respectively, for the irradiation through the substrate. As shown in the figure, the

Fig. 6. The dependency of the relative power gain of parasitic slot antenna arrays on the number of slots at 28 THz

power gain increased with the number of slots, as expected from the theory, and the power gain for the laser irradiation through the substrate improved by approximately 7 dB compared to the gain for the irradiation from the air-side. This value of 7 dB is due to the difference between the dielectric constant of the air and the ZnS substrate and agrees well with the theoretical value based on the transmission line model⁽¹⁴⁾. Furthermore, the power gain of the 7-parasitic slot antenna array improved by approximately 7 dB compared to the single-slot antenna for the laser irradiation both from the air-side and through the substrate.

4. Conclusions

We investigated the receiving properties of fabricated parasitic slot antenna arrays on ZnS dielectric substrates for 28-THz-CO₂ laser radiation. It was found that (1) the antenna theory based on the transmission line model was applicable and the slot antenna operated in the free space wavelength λ_0 at 28 THz, (2) the antenna receiving properties were affected by a dielectric constant, an absorption coefficient and the thickness of the substrate and (3) the power gain of the parasitic slot antenna arrays increased with increasing number of slots, and the power gain of the 7-parasitic slot antenna array improved by approximately 7 dB compared to that of the single-slot antenna. The antenna receiving properties were strongly affected by the thickness of the substrate as expected from the theoretical patterns. The thickness of the substrate is over 100 times longer than the dielectric wavelength of the irradiation at 28 THz, and it is difficult to control the thickness of the substrate precisely. In order to solve this problem, we must consider the substrate shape by, for example, changing the parallel plate to an extended hemispherical lens.

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References

- (1) D. Murphy, M. Ray, R. Wyles, J. Asbrock, N. Lum, J. Wyles, C. Hewitt, A. Kennedy, D. V. Lue, J. Anderson, D. Bradley, R. Chin, and T. Kostrzewa : "High Sensitivity 25 μ m Microbolometer FPAs", *Proc. SPIE*, Vol.4820, No.1, pp.208-219 (2002)
- (2) K. Hayashi, E. That, H. Wada, H. Higuma, and S. Miyashita : "Fabrication of Bi-La-Sr-Mn-O Uncooled Microbolometer", *Jpn. J. Appl. Phys.*, Vol.40, No.9A, pp.5281-5284 (2001)
- (3) S. Moon : "Novel Infrared Absorbing Material Coupled Uncooled Microbolometer", *Proc. IEEE Sensors 2004*, Vol.2, pp.658-660 (2004)

- (4) D. B. Rutledge, S. E. Schwarz, T. L. Hwang, D. J. Angelakos, K. K. Mei, and S. Yokota : "Antenna and Waveguide for Far-Infrared Integrated Circuits", *IEEE J. Quantum Electron.*, Vol.QE-16, No.5, pp.508-516 (1980)
- (5) C. Fumeaux, G. D. Boreman, W. Herrmann, H. Rothuizen, and F. K. Kneubuehl : "Polarization response of asymmetric-spiral infrared antennas", *Appl. Opt.*, Vol.36, No.25, pp.6485-6490 (1997)
- (6) G. P. Gautheir, J. P. Raskin, and G. M. Robeiz : "A 140-170 GHz low-noise uniplanar subharmonic Schottky receiver", *IEEE Trans. Microwave Theory Tech.*, Vol.48, pp.1416-1419 (2000)
- (7) Y. Yasuoka, T. Shimizu, Y. Abe, A. Kirihata, and K. Gamo : "Fabrication of Slot-Antenna Coupled Warm Carrier Detectors for Submillimeter Wave Radiation", *Jpn. J. Appl. Phys.*, Vol.38, No.9A, pp.5283-5286 (1999)
- (8) Y. Yasuoka, T. Sakurada, D. P. Siu, and T. K. Gustafson : "Resistance dependence of detected signals of MOM diodes", *J. Appl. Phys.*, Vol.50, No.9, pp.5860-5864 (1979)
- (9) N. Inoue, K. Harakawa, and Y. Yasuoka : "Characteristics of Schottky Diodes at 10.6 μm ", *Appl. Phys. Lett.*, Vol.42, No.3, pp.268-269 (1983)
- (10) Y. Yasuoka and T. Okuda : "Harmonic Mixing at 28 THz CO₂ Laser Frequency with Point-Contact Warm Carrier Devices", *Rev. Laser Engineering*, Vol.20, No.12, pp.37-43 (1992)
- (11) H. Kobayashi, Y. Abe, and Y. Yasuoka : "Slot-Array Receiving Antennas Fed by Coplanar Waveguide for 700 GHz Submillimeter-Wave Radiation", *IEICE Trans. Electron.*, Vol.E-82-C, No.7, pp.1248-1252 (1999)
- (12) T. Shimizu, Y. Abe, and Y. Yasuoka : "Thin-Film Slot Antenna for 700 GHz Submillimeter Wave Radiation", *IEICE Trans. Electron.*, Vol.E-78-C, No.8, pp.1002-1006 (1995)
- (13) Y. Abe and Y. Yasuoka : "Two-Dimensional Receiving Slot Antenna Arrays for 2.5 THz CH₃OH Laser Radiation", *Proc. IRMMW 2001*, pp.2-77-2-80 (2003)
- (14) H. Kobayashi, M. Yuki, and Y. Yasuoka : "Effects of Substrate Thickness on the Gain of Millimeter and Submillimeter Wave Slot Antenna", *IEICE Trans.*, Vol.J-80-B-II, No.1, pp.54-62 (1997)
- (15) T. Shimizu, Y. Abe, Y. Yasuoka, and K. Gamo : "Thin-Film Slot Antennas for 2.5 THz Submillimeter Radiation", *Jpn. J. Appl. Phys.*, Vol.35, No.2B, pp.L266-L268 (1996)
- (16) H. Kobayashi and Y. Yasuoka : "Slot-Array Antennas Fed by Coplanar Waveguide for Millimeter-Wave Radiation", *IEEE Trans. Microwave Theory Tech.*, Vol.46, No.6, pp.800-805 (1998)
- (17) Y. Abe, Y. Ohkubo, and Y. Yasuoka : "Receiving Properties of the Slot Antennas on the Substrate which Absorbs the Irradiated Electromagnetic Wave", *IEICE Trans.*, Vol.J84-C, No.3, pp.230-232 (2001)

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