Highly Directed Radiation Pattern From a THz Photonic Transmitter With a Two-Dimensional Rampart Slot Array Antenna

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Abstract—In this study, we investigate the directivity of the terahertz (THz) radiation pattern from a newly designed two-dimensional rampart slot array antenna integrated in an edge-coupled membrane photonic transmitter. The antenna design is based on the array theory which is well-developed in the microwave regime. By means of the array arrangement of rampart slot antennas, we demonstrate that the 3-dB beam width of the THz radiation pattern at 907 GHz is successfully confined within 30° in both H and E planes.

Index Terms—Antenna, array, radiation pattern, terahertz (THz) photonic transmitter.

I. INTRODUCTION

WITH the burgeoning terahertz (THz) wave applications such as molecule imaging system [1] and biodetection technology [2], how to collect THz waves more efficiently is a key point to design a THz wave source. We have previously demonstrated an edge-coupled photonic transmitter based on a low-temperature-grown GaAs metal-semiconductor-metal traveling-wave photodetector (MSM-TWPD) and a coplanar-waveguide (CPW)-fed slot dipole antenna. The compact THz source exhibited not only the wide frequency tunability but also the high conversion efficiency [3]. However, it is well known that the directivity of the radiation pattern, especially in the E plane, from the CPW-fed slot dipole antennas is low [4]. Therefore, the divergent THz

wave is not so appropriate for some far-field applications such as direct coupling to THz fibers without high numerical aperture focusing medium.

Many groups had been devoted to developing highly directed THz radiation sources with the array design such as photoconductive photomixer arrays [5] and photodiode-integrated antenna arrays [6]. However, multiple excitation sources are needed to drive each element in the array and this would make the system too complex for use. Arranging multiple devices in the array also makes the final circuit too large (usually several square millimeters to square centimeters) to be integrated with other circuits or devices.

To realize a compact highly directed THz wave source, here we demonstrate a new design for the THz photonic transmitter. A newly designed two-dimensional (2-D) rampart slot array antenna is adopted to centralize the main beam of the radiated THz waves. Combined with an edge-coupled MSM-TWPD, an ultra-high resonant frequency at 907 GHz could be observed. Under the coherently controlled optical beating excitation, the measured radiation pattern at 907 GHz is successfully concentrated to less than 30° in both the H and E planes, which is much smaller than the theoretical limit of a single CPW-fed slot dipole antenna [4]. By integrating the array antennas with a single photodetector, a highly directed THz wave emitter could be realized rather than combining multiple devices. The fabricated device size is less than 1 mm^2 , with a high capability for future integration in the optoelectronic integrated circuits and biomicrochips [2].

II. DESIGN AND STRUCTURE

The top micrographic view of the fabricated THz photonic transmitter is shown in Fig. 1. It is composed of an edge-coupled MSM-TWPD, a low-pass filter, a dc probe pad, and a newly designed array antenna. We adopt the MSM-TWPD as our photodetector due to its high-power bandwidth product [7] and superior microwave properties such as higher propagation velocity and lower high-frequency microwave loss [8]–[10]. The low-pass filter was designed by using a THz-wave photonic bandgap structure to reflect the THz-frequency ac currents back to the antenna to enhance the radiation efficiency. A detailed structure is shown in the inset of Fig. 1. The antenna was designed based on the array theory which is well-developed in the microwave regime. Since the excited THz signal is fed from the CPW after the TWPD, the design of our array antenna can be

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Fig. 1. Top micrographic view of the fabricated membrane photonic transmitter. The left-hand arrow indicates the direction of the coherently controlled quasi-CW optical excitation. The inset shows the detailed structure of the low-pass filter.

simplified without considering the excitation mechanism. As shown in Fig. 1, we arranged three CPW-fed rampart slot antennas in series with an interval of one guided wavelength ($\lambda_g = 156 \mu\text{m}$). The rampart slotline antenna was adopted due to several advantages including easy control of input impedance, small cross polarization level, and high gain [11]. Our rampart slotline has a $7\text{-}\mu\text{m}$ width for input matching while the length of both the vertical and horizontal segments equals to one half of the guided wavelength. Due to the magnetic current distribution in the slotlines, the far-field radiation pattern is only contributed from the vertical segments [11]. Thus, a linear array along the x -axis can be easily achieved by using a single rampart slot antenna and a more confined pattern in the $x-z$ plane (H plane) can be expected. However, the radiation pattern in the $y-z$ plane (E plane) from a single rampart slot antenna is still quite broad. To centralize the divergent radiation pattern in the $y-z$ plane (E plane), we arranged multiple rampart slot array antennas along the y -axis and separated them with an interval of one guided wavelength. Thus, a linear array in the other dimension could be achieved. Nevertheless, the antenna efficiency would saturate by adding too many elements in the x - or y -directions [11]. Considering a reasonable device size without sacrificing the efficiency, we choose three rampart pairs in the waveguide direction and eight radiating elements along rampart slotline pairs. We used a 3-D full-wave simulation tool, HFSS, to calculate the return loss and the radiation patterns of our array antennas. As shown in Fig. 2(a), our design had a good impedance match at 910 GHz. The corresponding radiation patterns in the E and H planes were shown in Fig. 2(b) and (c). The 3-dB beam width could be confined to $\sim 26^\circ$ in the E plane and $\sim 21^\circ$ in the H plane. Compared with the traditional CPW-fed slot dipole antenna [4], our new design attains higher directivity in both E and H planes. After combining all the designed elements, the size of the photonic transmitter is about 0.8 mm^2 .

III. EXPERIMENTAL SETUP AND RESULTS

We used a 800-nm femtosecond Ti:sapphire laser, with a 130-fs pulsewidth and a 82-MHz repetition rate, and a coherent control system to mimic a quasi-continuous-wave excitation [12], [13]. Before being guided into the Michelson interfer-

Fig. 2. (a) Simulated return loss of the 2-D array antenna. The impedance matching point is designed at 910 GHz. The simulated radiation patterns in the E and H plane at 910 GHz are shown in (b) and (c). The designed 3-dB beam width is about 26° and 21° , respectively.

Fig. 3. (a) Measured frequency response of the THz photonic transmitter. A relatively higher radiation power was observed at 907 GHz. (b) Bias dependence of the THz output power at 907 GHz. A $0.97\text{-}\mu\text{W}$ output power could be achieved under 4.5-mW optical excitation power and 28-V dc bias.

ometer, the femtosecond laser pulses were passed through a grating pair to be stretched in space and time according to their frequency. After precisely controlling the delay time of the two arms in a Michelson interferometer, we could control the overlap of two stretched pulses in the time domain and thus controlled the optical beating frequency of our excitation. The tuning range of our excitation frequency was up to 1.1 THz [3]. We focused the coherently controlled optical pulses into the absorption region of the photonic transmitter by a microscope objective. After excitation, we used two 3-in parabolic mirrors to collect the radiated THz wave and focused it into a liquid-He-cooled Si bolometer. The responsivity of the Si bolometer was calibrated with a method reported before [14]. We inserted a chopper in the optical path and measured the output of the bolometer with a lock-in amplifier. At a dc bias of 7 V and under 0.9-mW optical excitation power, the beating-frequency-dependent THz radiation power was measured and shown in Fig. 3(a). We could observe that there was a relatively higher radiation power at 907 GHz, which corresponds to our designed resonant frequency, within the 800- to 1000-GHz range. In addition, a strong resonant frequency at about 500 GHz was also observed and could be

Fig. 4. Measured radiation patterns (solid lines) at 907 GHz in the (a) E plane and (b) H plane. The simulated radiation patterns (open circles) in both planes at 910 GHz are also plotted for comparison.

attributed to the impedance mismatch at the 2λ resonant point [3]. The bias-dependent output power at 907 GHz under a fixed 4.5-mW optical excitation power was also measured. As shown in Fig. 3(b), a maximum average output power of $0.97 \mu\text{W}$ (corresponding to 1.3-mW peak power and 9-ps pulsewidth) could be achieved at a dc bias of 28 V. The corresponding external (including coupling and collection loss) power conversion efficiency is $0.97 \mu\text{W}/4.5 \text{ mW} = 2.14 \times 10^{-4}$, which agrees well with our previous results [3], [14], [15].

The THz radiation pattern was measured by a knife-cut method. A sharp metal plate was slid into the space between the photonic transmitter and the first collection mirror and its position was controlled by a stepping motor. Under a fixed optical excitation power of 0.9 mW and a dc bias of 7 V, the measured radiation patterns in the E and H plane at 907 GHz are shown in Fig. 4(a) and (b), respectively. The measured 3-dB beam width was successfully concentrated to $\sim 29^\circ$ and $\sim 27^\circ$ in the E and H planes. The simulated patterns at 910 GHz (open circles) are also plotted for comparison. Despite the finite collecting angle of the parabolic mirror, which was $\sim 90^\circ$ and $\sim 52^\circ$ in the E and H plane, respectively, most of the radiated THz waves could be collected. Therefore, the collection efficiency can be greatly enhanced by the present design. With the aid of the antenna array design, it becomes much easier to centralize and direct the THz output power to the expected region.

IV. CONCLUSION

We have demonstrated a novel THz photonic transmitter which is based on an MSM-TWPD and a CPW-fed 2-D rampart slot antenna array. A centralized THz radiation pattern in both H and E planes could be achieved without combining multiple THz sources. Our result shows the potential capability for radiation angle control and will be important for future

applications requiring a more confined radiation pattern, such as direct coupling to the THz fibers and some biodetection devices. The compact size ($< 1 \text{ mm}^2$) is also an advantageous feature for future integration with other active devices.

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