Frequency tunability of terahertz photonic transmitters

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In this study we investigated the frequency tunability of an edge-coupled membrane photonic transmitter. Its frequency tunability was found to be determined, not only by the radiation loss of the device and antenna pattern, but also by the frequency response of the photodetector. With a properly designed device pattern with a slot dipole antenna, which is known to have a strong resonant peak, both high-power conversion efficiency and a broadband response can be achieved. A wide frequency tuning range from <100 GHz up to 1.1 THz is demonstrated from a single terahertz photonic transmitter. Combined with coherent-controlled quasicontinuous-wave optical excitation, this optoelectronic-based device also exhibits a record-high light-THz power-conversion efficiency of 0.33%. © 2006 American Institute of Physics. [DOI: 10.1063/1.2176848]

To realize different terahertz (THz) wave applications, including molecule imaging and warfare inspection, a compact and high-efficiency continuous-wave (cw) THz source is highly desirable. Compared with other cw THz techniques such as Gunn diodes, *p*-type Ge-based or quantum cascade THz lasers, and resonant tunneling diodes, photomixing in low-temperature-grown GaAs (LTG-GaAs) photoconductors has the advantages of simplicity, room-temperature operation, tunable THz wavelength, and integrability with other semiconductor devices.^{1,2} Recently we have demonstrated an edge-coupled membrane photonic transmitter based on LTG-GaAs metal-semiconductor-metal (MSM) traveling-wave photodetectors (TWPDS).³ With a slot antenna, our previous device exhibited strong resonance with the antenna frequency and a high external light-THz power-conversion efficiency of 0.11% at the resonant frequency (645 GHz) was achieved,⁴ corresponding to an 64% external quantum efficiency while the optical coupling loss has not yet been corrected. Even though those previous devices showed promising performances, however, a device with slot dipole antennas is considered to have a narrow radiation bandwidth, and thus is not ideal for future spectral applications requiring wide frequency tunability.

Here we present the results of the frequency tunability study of the edge-coupled membrane photonic transmitter. The frequency tunability of our photonic transmitter is found to be determined, not only by the radiation loss of the device pattern but also by the frequency response of the MSM TWPDS. By tuning the designed device patterns, especially the patterns of the antenna and the low pass filter, one can determine the radiation loss of the device pattern and com-

bine it with the frequency response of MSM TWPDS to obtain the overall frequency response of the photonic transmitter. By optimizing the overall frequency tuning range of the photonic transmitter, we show that a device with a slot dipole antenna can achieve an ultrawide tunable bandwidth without losing its high conversion efficiency.

The demonstrated photonic transmitters were fabricated with a LTG-GaAs active region composed of an edge-coupled MSM-TWPDS,⁵ a coplanar-waveguide- (CPW-) fed slot antenna, a low pass filter, and a direct current (dc) probe pad, as shown in Fig. 1. The MSM-TWPDS was adopted due to its broad bandwidth⁵ and high-power-bandwidth product.⁶ The adopted antenna is a conventional slot dipole antenna with higher radiation power than the spiral antenna at the resonant frequency⁷ and was chosen for easy integration with the MSM-TWPDS, which has a CPW structure to support the photoexcited microwave-guiding mode. The low pass filter was designed by using a THz-wave periodic structure to im-

FIG. 1. The top view of the demonstrated photonic transmitter. Geometric information of the device is provided.

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FIG. 2. Device frequency response. Solid triangles represent the HFSS simulated radiation loss of the device pattern, solid circles are the designed frequency response of the photonic transmitter, and the open squares are the measured frequency response of the photonic transmitter.

prove its radiation efficiency at higher frequencies by reflecting the high-frequency alternating currents back to the antenna.

According to a previous study,⁵ the MSM-TWPD response degrades when the excited current frequency increases beyond 600 GHz. To increase the overall frequency tuning range, we designed the device patterns to enhance the radiation loss at the frequency range higher than 600 GHz to compensate for the low photodetector response. The first device pattern to be reconsidered is the slot antenna. The length of the slot determines the antenna resonant frequency while the width of the slot determines the antenna impedance. Both of these two parameters play key roles in the device performance. The second device pattern is the low pass filter, which also affects the resonant frequency and the impedance of the antenna. From the simulation, we have found that variation by 5% in geometry will not only lead to an obvious shift of the resonant frequency of the device pattern, but will cause significant impedance mismatch, which will also degrade the overall frequency tuning range. With the design, as shown in Fig. 1, the radiation loss of the device pattern, simulated by using a three-dimensional (3-D) full-wave simulation tool,⁸ is shown in Fig. 2. The antenna resonance frequency was designed to be 800 GHz with a shifted 2λ resonance frequency around 360 GHz and a 4λ resonance frequency around 200 GHz (not shown in the figure). The enhanced radiation around 400–500 GHz comes from the device structure resonance. Combining the radiation loss with the previously measured frequency response of the MSM-TWPD,⁵ the expected overall frequency response can be obtained and is also shown in Fig. 2. An extremely wide frequency tuning range, up to 1 THz, is expected.

In our measurement, we used femtosecond optical pulses and a coherent control method⁹ to mimic a quasicontinuous-wave excitation. A mode-locked Ti:sapphire laser (Spectra Physics Tsunami) was employed to produce 130 fs pulses with a repetition rate of 82 MHz at a central wavelength of 850 nm. By using a grating pair, pulses will become stretched in space and time according to their frequency. By precisely controlling the time delay of the two arms in a Michelson interferometer,⁹ we could control the overlap of the beams reflected from these two arms in the time domain at the output of the Michelson interferometer and thus con-

FIG. 3. THz power (solid triangles) and squared photocurrent (open circles) versus bias voltage for an input optical power of 1.87 mW.

trol the optical beating frequency of our excitation. After determining the excitation beating frequency, calibrated with an autocorrelator, the optical pulse was then focused into the absorption region of the photonic transmitter by a microscope objective. We used a liquid-helium-cooled Si bolometer to collect the THz waves from the device substrate side. By inserting a chopper in the optical path and measuring the output of the bolometer with a lock-in amplifier, the background noise could be minimized. The responsivity of the Si bolometer was calibrated with the same method reported in a previous work.³ At a dc bias voltage of 8 V and under a fixed excitation power of 1.33 mW, the beating-frequency-dependent THz power was measured and is shown in Fig. 2. A broadband response with a much-extended tuning range up to 1.1 THz can be found, confirming our device design. The curve of the measured response closely matches that of the simulated response with a resonant frequency of 800 GHz while a shifted resonant peak occurs at 400 GHz due to impedance mismatch at nonresonant points. Our experiments also indicated efficient radiation for frequencies lower than 300 GHz, thus making the practical effective range of the device shown in Fig. 1 as wide as 1.1 THz.

Figure 3 shows the measured bias-dependent output power (solid triangles) at 400 GHz under a fixed optical excitation (1.87 mW). The best measured external light-THz power conversion efficiency of 0.33% (without considering the optical coupling loss and THz collection loss) can be achieved at a 20 V bias voltage, where the collected THz power was $6.11 \mu\text{W}$. It is at least three times higher than our previously reported record value.⁴ It is important to notice that our reported power conversion efficiency is almost 3 times higher than that of a 100% quantum efficiency device operating under a similar photon condition. The power conversion efficiency of a 100% quantum efficiency device is equal to the THz photon energy-optical photon energy ratio, which is $400 \text{ GHz}/353 \text{ THz}=0.11\%$. Since our device is not an all-optical device, its corresponding quantum efficiency is thus not limited by 100%. With its THz radiation power proportional to the square of the excited photocurrent that is linearly proportional to the input optical power, our demonstration also shows the advantage of optoelectronic-based devices over all-optical devices in future THz applications, especially in the sub-THz regime. To confirm this point, we squared the measured bias-dependent photocurrents (open circles in Fig. 3) and compared them to the bias-dependent THz output power. These two curves overlap very well when the bias voltage is below 15 V. As the bias exceeds 15 V, these two curves begin to separate. We attribute this power

saturation phenomenon to the increased carrier lifetime of LTG-GaAs under high bias voltages.^{10,11}

In summary, the overall frequency response of a photonic transmitter is determined by the frequency response of the composed photodetector and the radiation loss of the device pattern, including the patterns of the antenna and low pass filter. After taking the frequency response of the MSM-TWPD into consideration, we intentionally designed the pattern of the photonic transmitter so that both high-power-conversion efficiency and ultrawide (up to 1.1 THz) tuning range can be simultaneously achieved, even though the antenna we adopted is a slot dipole antenna. This means that we do not need to use a broadband antenna to increase the frequency-tuning range while losing the radiation efficiency. By improving the antenna and device design, we successfully increased the frequency tuning range of the photonic transmitter up to 1.1 THz. In addition, a power conversion efficiency 3 times higher than that of a 100% quantum efficiency device was achieved under coherently controlled quasi-cw optical excitation. With such an ultrawide frequency tuning range and a high conversion efficiency, this compact and efficient broadband THz emitter can play cen-

tral roles in the future THz-based applications, including molecule spectral image and warfare inspection.

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