Investigation of Photoconductive Antenna Electrodes on Terahertz Signal Generation

Jose Santos and Magda El-Shenawee
Department of Electrical Engineering
University of Arkansas
Fayetteville, AR, United States
jisantos@uark.edu, magda@uark.edu

***Abstract*—This paper presents an investigation of terahertz (THz) signals generated using photoconductive antennas (PCAs) based on different electrode geometries. The geometry of the electrodes influences the shape of the THz pulse and its frequency spectrum. The geometry can be used to provide improvements to the bandwidth of the PCA. We used the transient solution of the RF module of COMSOL Multiphysics to simulate the radiated electric field based on using the photoconductive current as a time domain source in the gap of the antenna. The dimensions of a previously published bowtie H-dipole antenna were used as reference that was modified to three new configurations. The results show that the bowtie-H-dipole antenna provided broader bandwidth compared with the fractal, slot, and/or circular shape electrodes PCAs.**

Keywords—terahertz; photoconductive antenna; electrode geometry, THz pulse

I. INTRODUCTION

Terahertz (THz) photoconductive antenna (PCA) emitters are optoelectronic devices capable of transforming a femtosecond laser pulse into a time-domain pulse with frequency components in the THz range. Its conventional physical structure consists of metallic electrodes deposited on a semiconductor substrate separated by a gap where the laser source is focused. When the laser excitation is applied, some carriers are generated in the semiconductor, and they are driven to the electrodes by the application of a bias electric field. This flow of carriers produces a photocurrent that generates the THz pulse [1]. The research on PCA devices has been focused on improving some parameters such as efficiency and bandwidth. Some researchers have approached this issue by engineering the active area of the devices to improve the optical-to-THz conversion efficiency with the introduction of plasmonic nanostructures [2] while others have modified the geometry of these electrodes to improve the radiated power of these devices [3]. The shape of the THz pulse is dependent on the temporal profile of the photocurrent, which is dependent of the properties of the semiconductor material such as carrier mobility and carrier lifetime as reported in [4]. In the same way, the geometry of the PCA electrodes impacts the shape of the generated THz pulse and its spectrum. This work is focused on investigating different geometry modifications to the reference bowtie H-dipole antenna reported in [2] and [4], specifically the PCA's bandwidth.

This work was sponsored by the National Science Foundation (NSF) Award # 1948255.

II. METHODOLOGY

The commercial package COMSOL Multiphysics was used to simulate the THz signal generation from a PCA based on LT-GaAs. The geometry, dimensions, and model configuration of the PCA were based on the work reported in [4], where only one quarter of the geometry was simulated due to the symmetry of the devices. The photocurrent profile for the excitation of the model was obtained from a 2D electrical response solution for LT-GaAs at an average laser power of 1 mW and bias voltage of 30 V. LT-GaAs PCAs in a conventional configuration as shown in Fig. 2.1(a) with a 1.5µm half-space of air and 0.5 µm half-space of LT-GaAs. Gap 4 microns. The same excitation was used for all geometries presented here. The geometry of the electrodes for the signal generation reported in [4] was a bowtie H-dipole antenna, which serves as reference design for this work labeled as case ①. In this work, we investigate the effect that some modifications to the antenna structure produce on the generated THz pulse. Four cases are presented in this work, where three modifications were applied to the geometry used in [4]. The first modification is labeled as case ②, and it consists of the addition of fractals to the geometry presented in case ①. This type of fractals has been reported to improve the

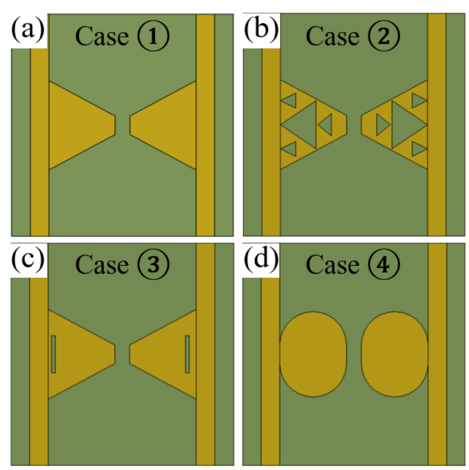

Fig. 1. Electrode geometry studied in this work. (a) Case ① with the same dimensions used in [4]. (b) Case ②: same dimensions of (a) with fractals [5]. (c) Case ③: same dimensions of (a) with slots [6]. (d) Case ④: Circular dipole [5].

THz radiated power [5]. Therefore, it was important to investigate its effect on the THz pulse shape. In case ③, slots were added to the geometry of case ①. The slots are used in other frequency bands to provide multiband operation [6]. Finally, case ④ changed the bowtie shape to a circular Apollonian dipole while keeping the H-dipole structure [5].

III. Results and Discussion

The results of the signal generation of the four geometries presented in Fig. 1 are shown in Fig. 2. Fig. 2(a) shows the time-domain generated THz pulse for each case, and Fig. 2(b) shows their frequency spectrum. The generated THz pulse in black labeled as case ① is the THz signal obtained from the reference geometry, and it resembles the pulse produced by the PCA presented in [4], where different semiconductor substrate was utilized. In other words, the signal produced by the photocurrent profile generated by two different materials with the same electrode geometry provided similar THz pulses. This supports the observation that the geometry of the electrodes significantly influences the shape of the THz pulse and so its frequency-domain spectrum. The pulse obtained from case ②, is shown in red-dashed line in Fig. 2(a), where its shape is very similar to the reference. The dip before the main pulse was amplified which explains its difference in spectrum, showing a narrower bandwidth. In addition, the amplitude of the time-domain THz pulse decreased by ~ 6.6% compared at the peak of the pulse against the reference case ①.

Case ③ is shown in Fig. 2 in blue dotted line which presented a larger difference compared to the reference pulse. In fact, its THz pulse showed s dip in its peak. This dip could be an effect of surface current reflections from the slot in the antenna which directly affected the peak of the pulse. In the same way, the spectrum was different compared to the reference, as it showed a resonance at lower frequencies around 3 THz, which could be explained by the multi-band operation that slots provide at other frequency bands [6]. This case ③ presented a higher magnitude of the spectrum at frequencies around 5 THz compared to all other cases. Finally, the pulse generated by case ④ is shown in Fig. 2 in green curve which is obtained from the circular H-dipole. Its generated THz pulse is very similar to the reference bowtie H-dipole geometry. However, as its pulse decreases from its peak, the pulse broaden producing a larger pulse width. This wider pulse width appeared in the spectrum by presenting a lower amplitude at frequencies around 2 THz compared to all other cases. However, its spectrum beyond 3 THz follows the spectrum obtained from the reference case ①.

IV. Conclusion

The studies presented in this work were oriented to investigate the effect of the electrode geometry on the generated THz pulse and its spectrum. Three modifications were developed from a previously reported bowtie H-dipole geometry. The introduction of fractals to the reference provided a narrower bandwidth. The application of slots to the reference bowtie h-dipole produced a resonance at lower frequencies. Finally, the spectrum of the circular H-dipole resembled the spectrum of the reference bowtie H-dipole at frequencies higher than 3 THz. Overall, all modifications presented in this work did not provide a significant advantage over the bandwidth of the geometry presented in [4].

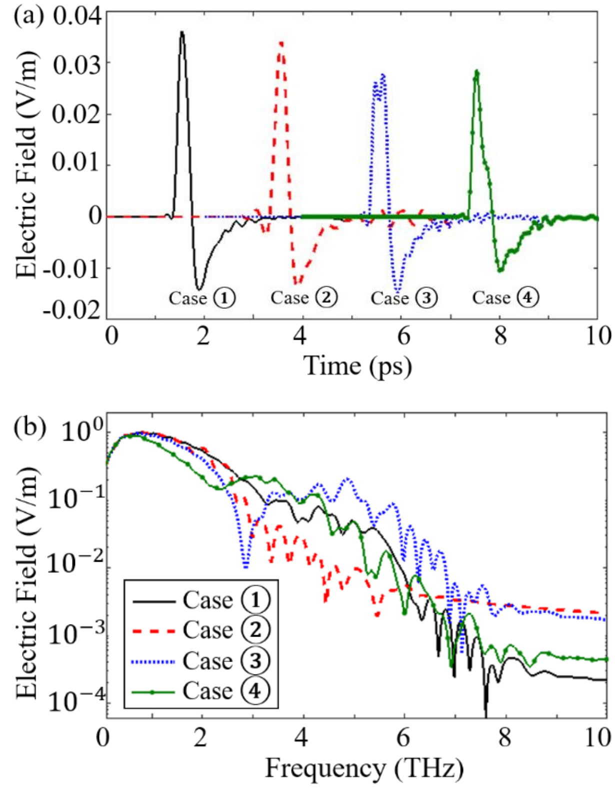

Fig. 2. Terahertz signal generation for different geometry electrodes presented in Fig. 1. (a) Time-domain generated THz pulse. (b) Frequency-domain spectrum of the pulses in (a).

References

[1] N. Burford and M. El-Shenawee, "Review of terahertz photoconductive antenna technology," *Optical Engineering* , vol. 56, no. 1, 2017.

[2] N. M. Burford, M. J. Evans and M. O. El-Shenawee, "Plasmonic Nanodisk Thin-Film Terahertz Photoconductive Antenna," *IEEE Transaction on Terahertz Science and Technology,* vol. 8, no. 2, pp. 237 - 247, 2018.

[3] C. W. Berry, M. R. Hashemi and M. Jarrahi, "Generation of high power pulsed terahertz radiation using a plasmonic photoconductive emitter array with logarithmic spiral antennas," *Applied Physics Letters,* vol. 104, no. 8, 2014.

[4] J. Santos Batista, H. O. H. Churchill and M. El-Shenawee, "Black phosphorus photoconductive terahertz antenna: 3D modeling and experimental reference comparison," *Journal of the Optical Society of America B,* vol. 38, no. 4, pp. 1367-1379, 2021.

[5] P. Maraghechi and A. Elezzabi, "Fractal Structures for THz Radiation Emitters," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 19, no. 1, 2013.

[6] H. Liu, H. Jiang, X. Guan, J. Lei and S. Li, "Single-Feed Slotted Bowtie Antenna for Triband Applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 12, pp. 1658-1661, 2013.