Capacitively-Loaded THz Dipole Antenna Designs with High Directivity and High Aperture Efficiency

Ning Zhu, and Richard W. Ziolkowski
Department of Electrical and Computer Engineering, University of Arizona
1230 E. Speedway Blvd.
Tucson, AZ 85721 USA

***Abstract*-Several linearly polarized photoconductive terahertz antenna designs and their performance characteristics are reported. A single capacitively-loaded dipole antenna is introduced first; it has a 12.8 dB directivity, a 11.6 dB realized gain, and a 82% radiation efficiency. By connecting two single capacitively-loaded dipole antennas to form a linear array, higher directivity (14.8 dB), lower sidelobe level (-18 dB) and larger front-to-back-ratio (14 dB) values are achieved. Moreover, by incorporating a meta-film structure as a superstrate of the antenna array, some additional interesting behaviors are achieved.**

IV. Introduction

Terahertz (THz) is the set of frequencies between the microwave and optical frequencies. Because THz imaging systems are able to provide images with higher resolution than microwave imaging systems and are non-ionizing so they also offer less potential harm to the human body than X-ray imaging systems, they have drawn greater attention recently, for instance, in quality control, non-destructive evaluation, medical, and security applications. As one of the most important components in a THz imaging system, the antenna is playing both impedance matching and power radiating roles. Some representative THz antenna examples can be found in [1-4]. While both photoconductive and photomixer style THz sources are being developed, we emphasize the former in all of the designs reported herein.

As the semiconductor across the photoconductive switch region (gap) is exposed to a laser beam, electron-hole pairs will be generated in it. If there is an external electric field across this photoconductive switch gap, usually generated between a DC voltage and ground, a current will be formed across it. If the laser signal has a short enough time period, i.e., roughly 100 femto-seconds, a THz signal will be generated by the resulting photoconductive current.

A single capacitively-loaded THz dipole antenna is initially designed to achieve the high directivity and high radiation efficiency properties desired for eventual application in a THz spectral imaging system. The capacitively-loaded structure also incorporates the necessary DC bias and ground lines. By connecting the DC bias and ground lines of two single capacitively-loaded THz dipole antennas together, an antenna array is generated. The impedance matching and performance characteristics of the array are fine tuned to achieve even more appealing radiation properties. In addition, the impact of the introduction of a meta-film structure-based superstrate into this array also will be analyzed. Since the aperture efficiencies for the original capacitively-loaded THz dipole antenna and the corresponding array are already over 100%, there is not much room to increase the directivity. Nevertheless, the presence of the superstrate provides additional design degrees of freedom which allow the increase of the front-to-back ratio value of the array at a trade-off cost of slightly increasing the side lobe levels of its radiation patterns. All the antennas in this paper were simulated with ANSYS/ANSOFT's high frequency structure simulator (HFSS).

V. Single Capacitively-Loaded Dipole Antenna Design

The single capacitively-loaded dipole antenna and its dimensions are shown in Fig. 1. The radiating element and ground plane are taken to be 0.35-μm-thick Ti-Au ($\sigma = 1.6 \times 10^7$ S/m). Both the substrate and the superstrate were selected to be GaAs ($\varepsilon_r = 12.9$, $\mu_r = 1.0$, loss tangent = 0.006). The substrate and superstrate thicknesses are 60 μm and 90 μm, respectively. The photoconductive gap region is located in the center of the figure. Because the femto-second laser beam must expose this gap region to generate the necessary electron-hole pairs, a truncated cone (frustrum) structure was cut through the ground plane and partially through the GaAs substrate to the expose the gap region. It has a 15 μm upper radius, a 20 μm lower radius, and 58 μm height. In order to assemble several single antennas into a THz antenna array, the DC bias and ground lines are designed to connect the edges of each single antenna. The four patch-like structures on the DC bias and ground lines represent the capacitive loadings of the dipole arms; they are introduced to achieve impedance matching. It is assumed that the power level of the incident laser beam will generate an effective 50 Ω source impedance. The design can be readjusted for other power levels and, hence, source impedances.

The simulation results show that the peak directivity of this single capacitively-loaded dipole antenna is 12.8 dB and the realized gain is 11.6 dB at 1.025 THz, a single-mode resonance with reasonable impedance matching. The radiation efficiency is 82% and the aperture efficiency is 144% [5]. Moreover, the 10dB bandwidth of this antenna is 0.071 THz at 1.025 THz, giving a fractional 10dB bandwidth: FBW_{10dB} =

7.1%. The corresponding far-field radiation pattern is shown in Fig. 2. One observes that the single THz antenna has a -7.7 dB sidelobe level and a 10 dB front-to-back ratio.

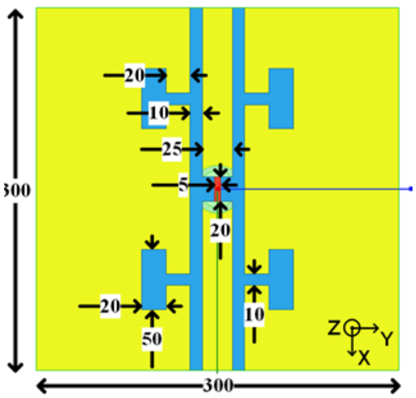

Figure 1. Single capacitively-loaded dipole antenna design. All dimensions are in μm.

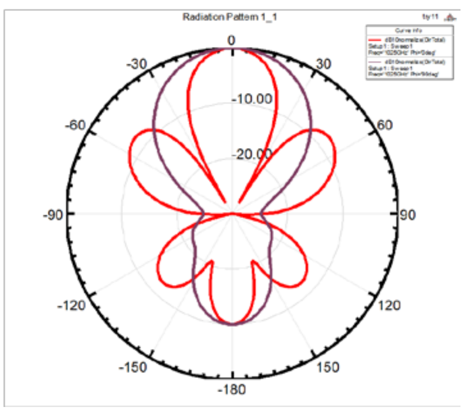

Figure 2. The E-plane (XZ) (red) and H-plane (YZ) (magenta) radiation patterns of the single capacitively-loaded THz dipole antenna at 1.025 THz.

VI. Capacitively-Loaded Dipole Antenna Array Design

By connecting the DC bias and ground lines of two single capacitively-loaded THz dipole antennas, one can generate a two element antenna array. This antenna array was then fine-tuned to achieve yet better antenna performance characteristics. The structure and dimension of the fine-tuned antenna array are shown in Fig. 3.

The simulation results predict that the peak directivity and realized gain are both increased by approximately 2 dB. A 77% radiation efficiency and a 120% aperture efficiency have been achieved. This aperture efficiency is slightly lower than the value for the single element system due to the increase in losses associated with the additional materials being present. Furthermore, the 10 dB bandwidth of the antenna array is now about 0.04 THz, which yields FBW_{10dB} = 4.0%. Fig. 4 shows the simulated radiation patterns of the antenna at its resonance frequency, 1.0 THz. These patterns have a -18 dB sidelobe level and 14 dB front-to-back ratio.

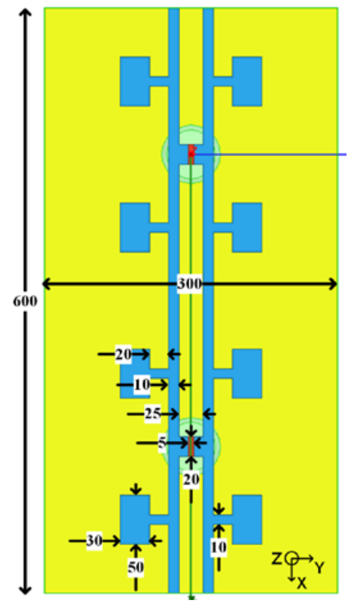

Figure 3. The two element capacitively-loaded THz dipole antenna array. All dimensions are in μm.

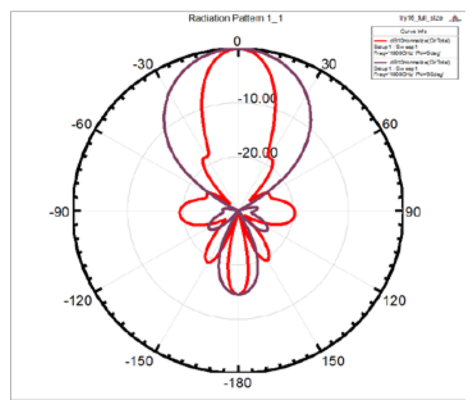

Figure 4. The E-plane (XZ) (red) and H-plane (YZ) (magenta) radiation patterns of the capacitively-loaded THz dipole antenna array at 1.0 THz.

VII. Superstrate-Augmented Two-element Capacitively-Loaded Dipole Antenna Array Design

A meta-film structure was selected as a superstrate for the two element capacitively-loaded THz dipole antenna array. It is based on the "I" elements used for an earlier epsilon-negative (ENG) metamaterial design [6]. Fig. 5 shows one example of this meta-film superstrate-augmented THz antenna array.

Some interesting behaviors were observed with the presence of the superstrate. The HFSS-predicted peak directivity and realized gain are 15.2 dB and 14.0 dB, respectively. Furthermore, a 77% radiation efficiency and 132% aperture efficiency have been achieved in this case. In addition, the

FBW_{10dB} = 4.0% at its resonance frequency 1.0 THz. The radiation pattern of this antenna at 1.0 THz is shown in Fig. 6. It illustrates that the simulated sidelobe level is now -15 dB, while the front-to-back ratio is now 29 dB. Since the original two element antenna array achieved over 100% aperture efficiency, this result confirms the expectation that it would be difficult to increase the directivity simply by using metamaterial-based superstrate. Moreover, because of this large aperture efficiency, the antenna array exhibits the expected relatively narrow directivity bandwidth. Nevertheless, this is a trade-off. In particular, when comparing Fig. 6 to Fig. 4, one immediately finds that the meta-film superstrate structure is able to increase the front-to-back ratio value of the array at a trade-off cost of slightly increasing the side lobe levels of its radiation patterns.

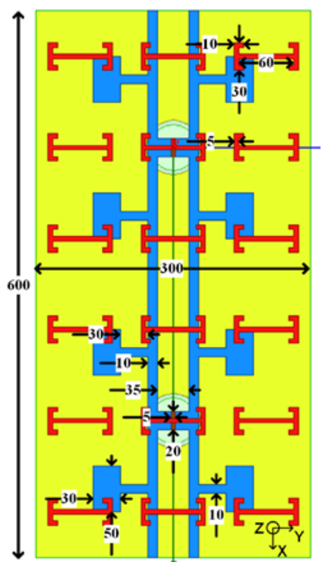

Figure 5. The meta-film superstrate augmented, two-element capacitively-loaded THz dipole antenna array. All dimensions are in μm.

V. Conclusions

In this paper, we designed several capacitively-loaded THz dipole-based antennas. All of these antennas were shown to achieve high directivity, resulting in over 100% aperture efficiency at resonance frequencies near 1.0 THz. It was demonstrated that a two-element array based on this single dipole element achieved about a 2 dB increase in directivity and gain. By augmenting the two-element array with a meta-film superstrate structure, the resulting antenna system was shown to have a further increase in its front-to-back ratio value of the array at a trade-off cost of slightly increasing the side lobe levels of its radiation patterns.

These simulation results have confirmed that the single capacitively-loaded THz dipole antenna will be an eligible candidate for our THz photoconductive antenna array. In particular, they have demonstrated that all the DC bias and ground lines can be easily connected together without impacting negatively the performance of the antenna system. We hope to report more design and simulation results in our presentation.

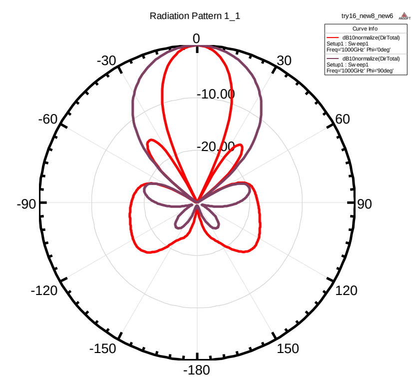

Figure 6. The E-plane (XZ) (red) and H-plane (YZ) (magenta) radiation patterns of the meta-film superstrate-augmented two element capacitively-loaded THz dipole antenna array at 1.0 THz.

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