Multiphysics Modeling of THz Photoconductive Antennas

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***Abstract*—A new method for modeling terahertz photoconductive antennas (THz-PCAs) is presented. The finite element method solver COMSOL® is utilized to combine Maxwell's, Poisson's and the Drift-Diffusion equations into a single 2D/3D multiphysics model. This model can then be used to computationally investigate and design THz-PCAs with more complex geometries compared with current numerical methods. Preliminary results show good agreement between the proposed model and the standard analytical methods for calculating photocurrent generation in THz-PCAs, as well as supporting previously reported experimental observations.**

I. INTRODUCTION

SINCE the development of stable room-temperature sources, THz technology has seen rapid increase in applications and development. Imaging for medical and industrial applications as well as spectroscopy for material characterization and detection are some of the promising applications for this technology. Pulsed THz systems in particular have generated much interest due to the wide bandwidth and unique depth information they can acquire. However, low power (≈1μW) of the emitted pulses limits the penetration depth that can be achieved [1]. This low pulse power arises from the inefficiency in which traditional THz-PCAs are able to convert optical pump power to the narrow photocurrent pulses needed to generate THz.

Recently, advanced plasmonic THz-PCA designs have been proposed. By increasing the area in which the antenna electrode and incident laser pulse are able to interact, these antennas have experimentally demonstrated up to two orders of magnitude increase in emitted THz power over conventional designs [2]. Drude-Lorentz based models for THz sources do not take into account the geometric structures that lead to this enhancement [3]. This work proposes to implement a 2D/3D finite element model using COMSOL Multiphysics which includes the time dependent optical response, carrier transport and electrical characteristics for the design of plasmonic enhanced PCAs.

The model consists of two coupled studies; first the optical response is calculated in the frequency domain using the electromagnetic wave equation (1).

$$\nabla \times \mu_r^{-1}(\nabla \times \boldsymbol{E}) - k_o^2\left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_o}\right)\boldsymbol{E} = 0 \tag{1}$$

The pump source is modeled as a focused monochromatic Gaussian beam at a wavelength of 800 nm. From here it is possible to calculate the Poynting vector, and as such the photon absorption flux inside the PCA substrate. The advantage with incorporating this step into the model is that the photon absorption flux is non-uniform in the PCA substrate. Although approximations of uniform absorption has been shown to work for traditional THz-PCAs, it is well known that plasmonic photoconductive devices have an extremely non-uniform electric field distribution with much of the electromagnetic energy strongly concentrated near the plasmonic structure [2].

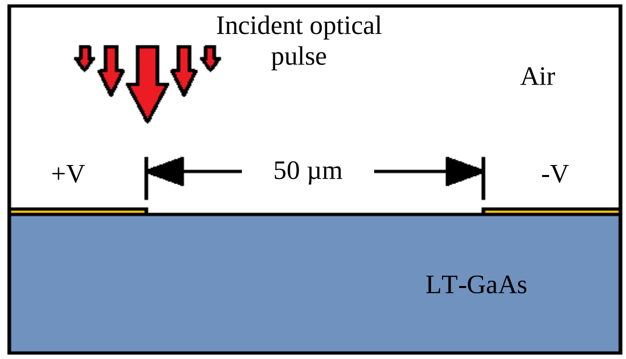

Fig. 1. Illustration of the two dimensional computational setup studied in this work. Two electrodes are located on the top of a LT-GaAs substrate with 50 μm spacing between. The Gaussian optical pulse is incident from the top of the domain and centered on the positive biased electrode.

The second study determines the carrier dynamics due to the applied bias $\boldsymbol{V}$ and the optical carrier generation $U_{n,p}$. The peak carrier generation is taken from the photon absorption flux calculated in the optical study and approximated to have Gaussian time dependence. The temporal width of the pulse corresponds to the width of the femtosecond laser pulse (FWHM ≈ 100 fs). The equations governing these carrier dynamics in the semiconductor layer are Poisson's equation (2) and the carrier transport equations for electrons (3) and holes (4).

$$\nabla \cdot (\epsilon_r \nabla \boldsymbol{V}) = q(\boldsymbol{n} - \boldsymbol{p} + N_A - N_D) \tag{2}$$

$$\frac{\partial \boldsymbol{n}}{\partial t} = -\frac{1}{q}\nabla \cdot \boldsymbol{J}_n - U_n \tag{3}$$

$$\frac{\partial \boldsymbol{p}}{\partial t} = \frac{1}{q}\nabla \cdot \boldsymbol{J}_p - U_p \tag{4}$$

Here, $\boldsymbol{n}$ and $\boldsymbol{p}$ are the electron and hole densities and $\boldsymbol{J}_{n,p}$ is the electron/hole current density. The current density is a function of the electron/hole concentration, material properties and the applied potential $\boldsymbol{V}$. Equations (2-4) then are directly coupled through $\boldsymbol{V}$, $\boldsymbol{n}$ and $\boldsymbol{p}$ while equation (1) determines the spatial distribution of $U_{n,p}$ which is a function of time only.

II. RESULTS AND DISCUSSION

The proposed model was utilized to calculate the time dependent photocurrent collected by a traditional (non-plasmonic) PCA, similar to the antenna investigated in [3]. An illustration of the two-dimensional computational setup is shown in Fig. 1. Two electrodes are located on opposite ends

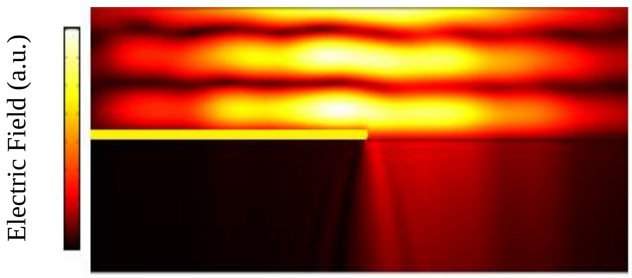

Fig. 2. Electric field distribution at the positive biased electrode due to an incident optical pump with a Gaussian distribution in the horizontal dimension (full computational domain not shown).

of a low temperature grown gallium arsenide (LT-GaAs) substrate, with a 50 µm separation. The incident optical pulse is centered above the edge of the positive biased electrode and is focused to a spot size (HPBW) of 5 µm. As previously stated, the first step in the model is to calculate the electromagnetic response due to the incident optical excitation. Fig. 2 illustrates the results of this step. The magnitude of the electric field is plotted in the air-positive electrode-semiconductor region, approximately the left half of the domain illustrated in Fig. 1. Here the Gaussian spatial dependence of the incident excitation can be seen in the top air region. In the LT-GaAs region it is noted that the distribution of the transmitted electric field is non-uniform.

Comparison results utilizing this model are shown in Fig. 3. From the non-uniform field distribution illustrated in Fig. 2, the carrier generation rate $U_{n,p}$ is determined and by solving equations (2-4), the time dependence of the current collected at the positive biased electrode can be calculated. Here, the solid trace represents the normalized photocurrent collected at the antenna electrode calculated utilizing the current model, while the circles represent previously published results using the Drude-Lorentz model [3]. Good agreement in the time-domain behavior of the collected photocurrent is observed between the two models. This indicates that 3D multiphysics modeling for THz-PCAs will be a promising method for analyzing more complex PCA configurations.

A second study was performed to illustrate the advantage of the current model. Previously reported experimental results have shown that the optimal location of the optical pulse for these types of THz antennas is centered on the edge of the

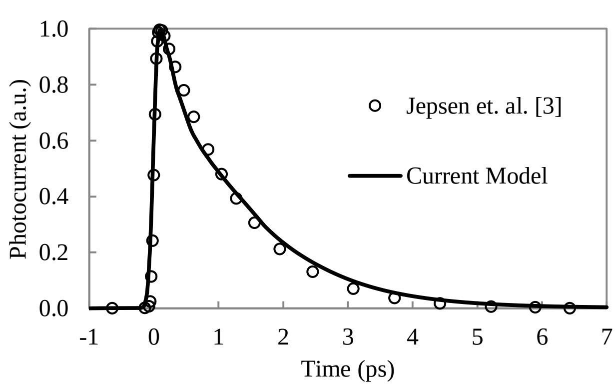

Fig. 3. Normalized photocurrent generation in a THz-PCA versus time due to an incident femtosecond laser pulse calculated using our model (solid trace) and the Drude-Lorentz model (circles) results from [3].

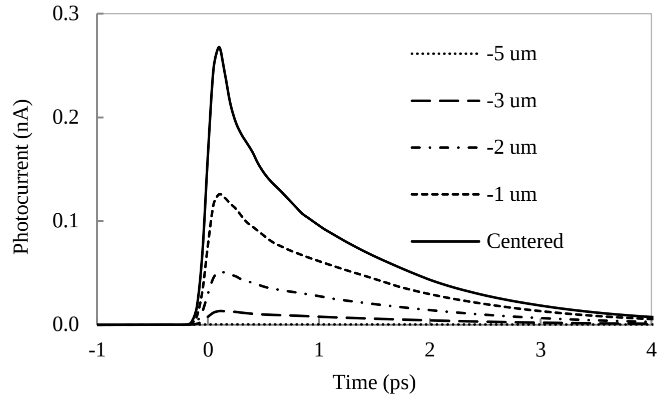

Fig. 4. Collected photocurrent versus time at the positive biased electrode calculated using the current model for varying distance of the incident optical pulse from the electrode.

positive biased electrode, as is illustrated in Fig. 1. As the pulse is centered further from the electrode the THz power emitted by the antenna drastically reduces [4]. This behavior is verified using the current model and the results are illustrated in Fig. 3. Here it is observed that with increasing distance of the optical pulse from the electrode the peak in the collected photocurrent pulse reduces by more than half for every 1 µm increase in distance from the electrode. In addition to a reduced peak current, the pulse becomes increasingly broadened in time, which reduces the amount of high frequency (THz) energy the pulse carries. These two mechanisms indicate that there will be a drastic decrease in THz power emitted by the antenna.

III. Summary

We have proposed a new multiphysics model for THz-PCAs and preliminary results in calculating the time-dependent photocurrent generation show good agreement with the standard Drude-Lorentz model. Additionally, the model has demonstrated the dependence of the collected photocurrent on the location of the optical excitation, with the modeled behavior supporting previously reported experimental results. Future work will aim to further validate the model with additional experimental results. This model will then be expanded from 2D to 3D and used to analyze complex plasmonic THz-PCAs.

References

[1] Daryoosh Saeedkia, *Handbook of Terahertz Technology for Imaging, Sensing and Communications*. Cambridge: Woodhead Publishing Limited, 2013.

[2] C Berry, N Wang, M Hashemi, M Unlu, and M Jarrahi, "Significant Performance Enhancement in Photoconductive Terahertz Optoelectronics by Incorporating Plasmonic Contact Electrodes," *Nature Communications*, vol. 4, no. 1622, pp. 1-10, March 2013.

[3] P Jepsen, R Jacobsen, and S Keiding, "Generation and Detection of Terahertz Pulses from Biased Semiconductor Antennas," *J. Opt. Soc. Am. B*, vol. 13, no. 11, pp. 2424-2436, November 1996.

[4] S, E Ralph and D Grischkowsky, "Trap-enahnced Electric Fields in Semi-insulators: The Role of Electrical and Optical Carrier Injection," *Appl. Phys. Lett.*, vol. 59, no. 16, pp. 1972-1974, October 1991.