

# Terahertz Photo-conductive Antenna Array Power Scaling Simulations

Joseph M. Koning\*

Lawrence Livermore National Laboratory, Livermore, CA,  
koning1@llnl.gov

## Introduction

The creation and propagation of Terahertz pulses has become increasingly important in today's world. Terahertz sources are used in varied fields including security screening, biological evaluation and spectroscopy. These fields all benefit from Terahertz sources with large power output. The specific source of Terahertz radiation studied in this paper is the Auston switch [1]. A single Terahertz producing photoconductive Auston switch suffers from lack of power due to limitations in optical power conversion and maximum bias voltage. The power limitations may be overcome by using an array of photoconductive switch antennas for power scaling. The array is evaluated with possible power differences due to asynchronous laser pulses. The method used to evaluate these antennas is the differential forms finite element method [2]. The lowest order mass-lumped, Nedelec basis functions are used on a Cartesian grid for efficiency. In this configuration the method is comparable in speed with the FDTD method but can also be configured for unstructured grids.

## Method

The three dimensional second-order Maxwell's wave equation for the vector field  $E$ , is used for the antenna simulations.

$$\bar{\epsilon} \frac{\partial^2}{\partial t^2} E + \bar{\sigma} \frac{\partial}{\partial t} E = -\nabla \times \frac{1}{\bar{\mu}^{-1}} \nabla \times E - \frac{\partial}{\partial t} J_s, \quad (1)$$

$$E \times \hat{n} = E_{bc} \text{ on } \Gamma_D, \quad (2)$$

$$E(t=0) = E_{ic}, \quad \frac{\partial}{\partial t} E(t=0) = \frac{\partial}{\partial t} E_{ic} \quad (3)$$

$$\frac{\partial}{\partial t} B = -\nabla \times E \quad (4)$$

here  $\Gamma_D$  is the part of the boundary of the region  $\Omega$  where Dirichlet boundary conditions are applied. Note that  $J_s$  is an independent current source term. The material properties  $\bar{\epsilon}, \bar{\mu}, \bar{\sigma}$  are in general real symmetric positive definite tensors that are inhomogeneous in space and time dependent.

The vector wave equation (1) is solved by the three-dimensional, parallel electrodynamics code *EMSolve* [3], using the discrete differential forms finite element method. It is a simple matter to also compute the magnetic field by integrating the Faraday equation (4). At present, our solution to (1),(4) is explicit, with a time step restriction  $\Delta t = O\left(\frac{\Delta h}{c}\right)$ , where  $c$  is the speed of light in the medium of interest, and  $\Delta h$  is the smallest element dimension in the mesh.

In equations (1) and (4), the electric and magnetic fields are expanded in terms of the lowest order Nedelec edge and face elements. The domain in these simulations is an orthogonal, Cartesian grid. When the mesh is restricted to this geometry an efficient formulation for the basis functions on hexahedral elements can be used called the Mass-Lumped basis functions [4]. These basis functions reduce mass matrix to a diagonal matrix which can be easily inverted for efficient solutions. Even though the geometry in this paper is an orthogonal, Cartesian grid, the method is still fully applicable for arbitrary domains. In this case the mass matrix is no longer diagonal but is still more sparse than a fully consistent mass matrix.

The outer domain boundary is terminated through the use of the first order Sommerfeld absorbing boundary conditions. The impedance for each material is included separately into a matrix defined on the boundary and included on the right hand side of the system.

## Results

The simulation domain is shown in Figure 1 with dimensions 200x600x300 micrometers. The domain is separated into three subdomains. The first domain is the air region defined by the lower 100 micrometers in the z-direction. The subdomain above the air region is modeled as a GaAs semiconductor with relative dielectric  $\epsilon_r = 12.6$ . The final domain is the antenna region. This region is an array of three antennas modeled as metal deposited on the semiconductor surface. The metal surface of the antennas is defined as a PEC surface. This surface surrounds a void within this antenna region. The thickness of the metal in the z-direction is 10 micrometers. A mesh spacing of 10 elements per wavelength for a target wavelength of 200 micrometers is used in the Cartesian grid. The spacing between each antenna is 100 micrometers which is half the target wavelength. Each antenna has a source region between defined between the the antenna gap. This antenna gap has a length of of 35 micrometers. The antenna region is closed on each end to eliminate charge build up.

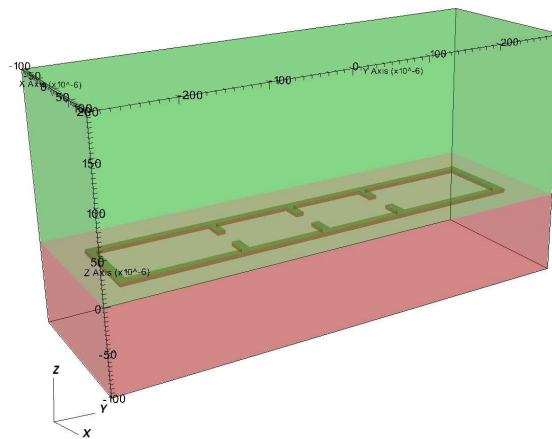


Figure 1: The multi-antenna geometry.

The current density pulse source,  $J_s$ , resulting from the photo-generation via a femtosecond laser, is modeled by a Gaussian pulse with FWHM of 140 femtoseconds. This pulse is applied to the antenna gap region for each of the antennas independently. The electric field magnitude for simulation with three applied current pulses with pulse delay is shown in Figure 2.

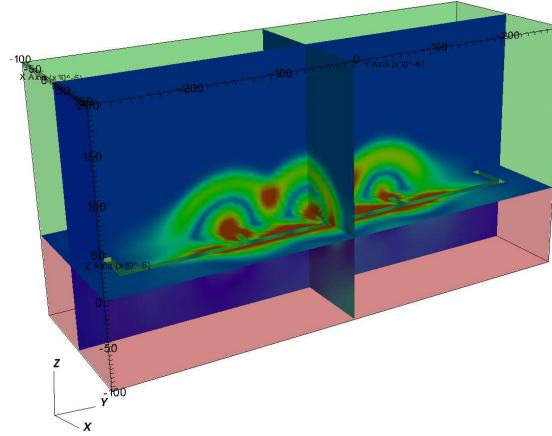


Figure 2: The electric field magnitude at t=0.8 picoseconds.

A series of simulations for constant geometry and a single antenna or multiple antennas have an applied current density. The power versus time for the each of these simulations at a plane 150 micrometers above the antenna is shown in Figure 3. The power is given in arbitrary units and follows the n-squared power law scaling with an actual slope of 1.7. The ringing due to the closed antenna system is evident in the power plots.

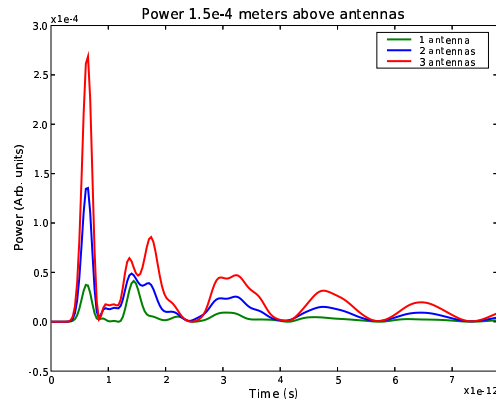


Figure 3: Power for the three antenna configurations.

The power for the same configurations with a 10% time delay shift between the current density pulses is shown in Figure 4. The antenna in the positive y-direction from center had a 10% increase in the pulse delay while the antenna in the negative y-direction from center had a 10% decrease in the pulse delay. This slight delay shows no decrease in the power output for the antenna configuration.

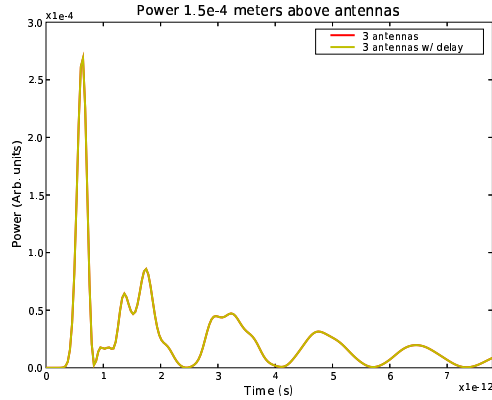


Figure 4: Power for the three antenna configurations with 10% time delay.

## Conclusion

Measurements for multiple photoconductive switch arrays have been performed using an accurate and efficient finite element method for the second order wave equation using mass lumped basis functions. These simulations confirm the ability of an array of photoconductive antennas to increase the output power even with slight time delays in the current density source. Future work will include antenna geometry variations and the inclusion of a carrier dynamics solver for more accurate system power measurements.

## References

- [1] Smith P.; Auston D.; Nuss M., "Subpicosecond Photoconducting Dipole Antennas", IEEE J. Quantum Elect., v. 24, n. 2, pp. 255-260, 1980.
- [2] Castillo P.; Koning J.; Rieben R.; White D., "A discrete differential forms framework for computational electromagnetics," Comp. Meth. Eng. Sci. Vol 5 No 4 pp 331 346, 2004.
- [3] White D.A.; Koning J.; Rieben R.N.; Stowell M.; Fisher A.; Fasenfest B.; Rodrigue G.H., "EMSolve", <http://www.llnl.gov/casc/emsolve>.
- [4] Fisher, A.; Rieben, R.N.; Rodrigue, G.H.; White, D.A., "A generalized mass lumping technique for vector finite-element solutions of the time-dependent Maxwell equations," Antennas and Propagation, IEEE Transactions on , vol.53, no.9, pp. 2900- 2910, Sept. 2005.