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Using COMSOL Multiphysics Software to Model Anisotropic Dielectric and Metamaterial Effects in Folded-Waveguide Traveling-Wave Tube Slow-Wave Circuits

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Abstract

The electromagnetic effects of conventional dielectrics, anisotropic dielectrics, and metamaterials were modeled in a terahertz-frequency folded-waveguide slow-wave circuit. Results of attempts to utilize these materials to increase efficiency are presented.

Introduction

COMSOL Multiphysics (ref. 1) is a versatile commercial software package that solves systems of coupled three-dimensional partial differential equations. Thus it can be used to model physical phenomena in a wide range of applications including electromagnetics. With the finite element method of solution, it can easily model complex material properties that cannot readily be modeled with finite difference codes. For our interests in particular, it can solve for the electromagnetic fields in devices that include anisotropic dielectrics or metamaterials with negative values for electric permittivity and/or magnetic permeability.

We will confirm that COMSOL Multiphysics can accurately determine the dispersion and interaction impedance for slow-wave circuits. We will then show that it can be used to investigate electromagnetic effects of both conventional dielectrics and unconventional materials such as anisotropic dielectrics and metamaterials. In particular, we will show results of attempts to improve the design power and efficiency of a terahertz-frequency folded-waveguide slow-wave circuit.

Background

There is much interest in using vacuum electronic amplifiers in the terahertz regime of the electromagnetic spectrum because of their superior power and efficiency capabilities compared to solid state power amplifiers (SSPA's) at high frequencies (ref. 2). However, power and efficiency levels with conventional vacuum electronics devices are still quite low at these frequencies because of the small size of the circuit dimensions and high attenuation (ref. 3).

In attempts to reduce the attenuation and improve power and efficiency at terahertz frequencies, we modeled and investigated the effects of conventional dielectrics, anisotropic dielectrics, and metamaterials with negative values of electric permittivity and/or magnetic permeability (refs. 4 and 5) in a metallic folded-waveguide slow-wave circuit. The COMSOL Multiphysics finite element software package was utilized because its flexibility enables it to model material properties that are difficult to model with finite difference codes.

Analysis and Results

To test its accuracy, COMSOL Multiphysics's RF Module was used to compute the dispersion and interaction impedance for ferruleless and ferruled coupled-cavity slow-wave circuits. The agreement with experiment was comparable to that obtained previously with other software (refs. 6 and 7). It was then used to model the dispersion, interaction impedance, and attenuation for the folded-waveguide slow-wave circuit shown in figure 1 operating at a frequency of 0.4 THz. Figure 2 shows the computed surface current densities on the conducting waveguide walls for half of a geometric period. Because the current density and corresponding ohmic loss is strongest along the inside curves of the waveguide, we experimented with replacing the metal with nonconducting materials in these regions.

We first modeled the dielectric silicon on the inner curve surfaces. Although it would be difficult, in principle this structure could be fabricated with a dielectric-metal layered structure. At 0.4 THz, the computed attenuation dropped 45 percent, but unfortunately the interaction impedance dropped by 60 percent, resulting in a decrease in estimated circuit efficiency. We next investigated the effects of anisotropic dielectrics in which the permittivity is directionally dependent. However, scanning over the permittivity tensor components showed no improvement over the isotropic case.

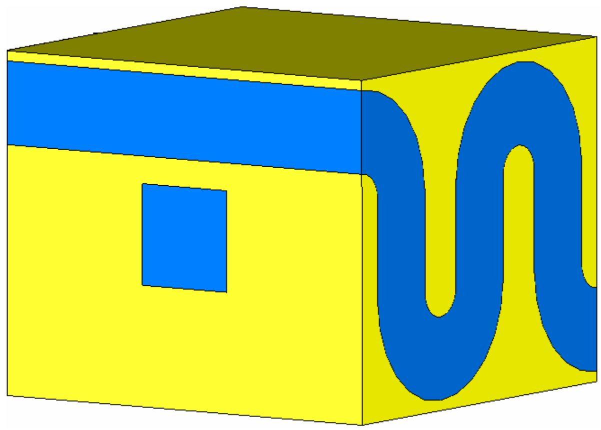

Figure 1.—Section of folded-waveguide slow-wave circuit. Electron beam passing through square aperture interacts with electromagnetic wave passing through serpentine waveguide.

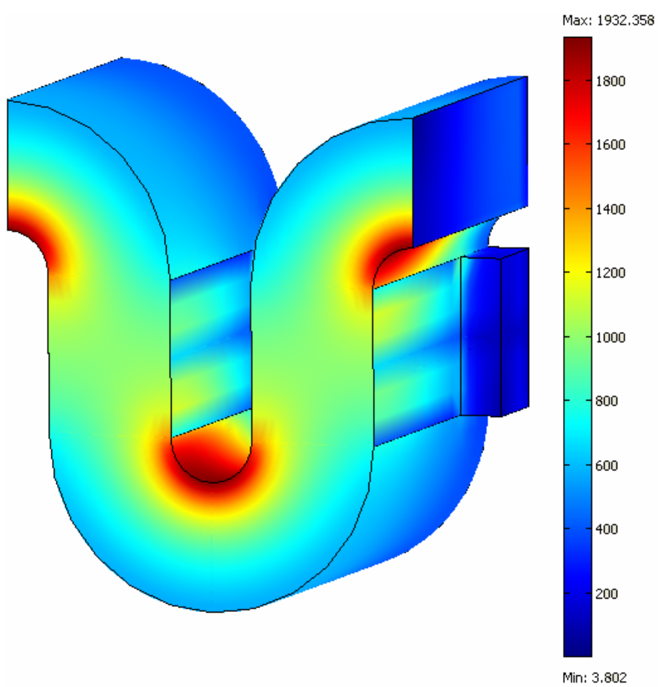

Figure 2.—Computed surface current densities for half of a geometric period of folded-waveguide slow-wave circuit.

Finally we investigated metamaterials. These engineered non-natural materials have been shown recently to exhibit effective negative values for permittivity and permeability at microwave frequencies (refs. 4 and 5). We did determine that the efficiency could be improved for small conductivity values when permittivity and permeability have opposite signs and small values. It is possible that future developments in metamaterial theory and nanofabrication could make such material characteristics possible in the future. However present metamaterials have high attenuation and there is as of yet no known method of fabricating such a hypothetical low-loss metamaterial.

Conclusion

We were not able to design for a significant improvement in computed power or efficiency by utilizing either conventional dielectrics, non-isotropic dielectrics, or existing metamaterials in terahertz folded-waveguide slow-wave circuit designs. Barring future major advances in metamaterial theory and nanofabrication, it appears that this is not a useful path toward efficiency and power improvement. However, we were able to show that COMSOL Multiphysics is a useful tool for investigating unconventional materials in electromagnetic devices. In the future, this modelling capability may be able to show that such materials can provide significant advantages in other applications.

References

1. http://www.comsol.com.
2. J. Booske, D. Whaley, W. Menninger, R. Hollister, and C. Armstrong, "Traveling-Wave Tubes," in *Modern Microwave and Millimeter-Wave Power Electronics*, R. Barker et al., eds. New York: Wiley-Interscience, chap. 4, 2005.
3. G. Scheitrum, "Microfabricated MVEDs," in *Modern Microwave and Millimeter-Wave Power Electronics*, R. Barker et al., eds. New York: Wiley-Interscience, chap. 7, 2005.
4. D. Smith, *et al.*, "Composite Medium with Simultaneously Negative Permeability and Permittivity, *Phys. Rev. Letters*, May 1, 2000.
5. J. Wilson and Z. Schwartz, "Multifocal Flat Lens With Left-Handed Metamaterial," *Applied Physics Letters*, Jan. 10, 2005.
6. D. Schroeder and J. Wilson. "Ferruleless Coupled-Cavity Traveling-Wave Tube Cold-Test Characteristics Simulated with Micro-SOS," NASA TP–3306, Aug. 1993.
7. J. Maruschek, C. Kory, and J. Wilson. "Generalized Three-Dimensional Simulation of Ferruled Coupled-Cavity Traveling-Wave Tube Dispersion and Impedance Characteristics," NASA TP–3389, Nov. 1993.

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