METAMATERIAL-LOADED WAVEGUIDES FOR ACCELERATOR APPLICATIONS

S. Antipov, L. K. Spentzouris, IIT, Chicago IL, 60616, U.S.A.
M. Conde, W. Gai, W. Liu, R. Konecny, J. G. Power, Z. Yusof, ANL, Argonne, IL, 60439, USA

Abstract

Metamaterials (MTM) are artificial periodic structures made of small elements and designed to obtain specific electromagnetic properties. As long as the periodicity and the size of the elements are much smaller than the wavelength of interest, an artificial structure can be described by a permittivity and permeability, just like natural materials. Metamaterials can be customized to have the permittivity and permeability desired for a particular application. Waveguides loaded with metamaterials are of interest because the metamaterials can change the dispersion relation of the waveguide significantly. Slow backward waves, for example, can be produced in an LHM-loaded waveguide without corrugations. In this paper we present theoretical studies and computer modeling of waveguides loaded with 2D anisotropic metamaterials, including the dispersion relation for a MTM-loaded waveguide. The dispersion relation of a MTM-loaded waveguide has several interesting frequency bands which are described. It is shown theoretically that dipole mode suppression may be possible. Therefore, metamaterials can be used to suppress wakefields in accelerating structures.

INTRODUCTION

The electromagnetic properties of a medium are characterized by the permittivity ε (response to electric field) and the permeability μ (response to magnetic field). Typically ε and μ are positive for most frequencies of electromagnetic waves. In this case, the phase vector (k) of the wave forms a right-handed system with the field vectors E and B. The Poynting vector is co-directed with k.

V. Veselago first pointed out that propagation is also possible when ε and μ are simultaneously negative [1]. Propagating waves in such double-negative media (DNM) exhibit several unusual properties. First of all, the phase vector forms a left-handed system with the field vectors. This is why materials with simultaneously negative ε and μ are also called left-handed (LHM). In such media the Poynting vector, which is collinear with the group velocity, is counter-directed to the phase vector. This gives rise to several unusual effects like the reversed Doppler effect, reversed Cherenkov radiation (CR) [1, 2 and 3] and negative refraction [1, 4]. Cherenkov radiation is widely used in accelerator physics. It has particle detector applications and it may be that reverse Cherenkov radiation is uniquely useful for beam detection [2, 3 and 5].

At Argonne Wakefield Accelerator Facility (AWA) we are focused on studies of particle interaction with metamaterials. We have designed and manufactured a double-negative metamaterial similar to others [6]. In [5, 7] we reported our first metamaterial design. We used a known method [4] to experimentally verify that the refraction of our left-handed metamaterial is negative. We also performed a standard [8] left-handed transmission measurement for both the configuration of a bulk metamaterial and for a metamaterial-loaded waveguide [9]. We observed much better transmission level and stability to manufacturing tolerances for a loaded waveguide. Thus, we are using a metamaterial-loaded waveguide configuration for our further studies. In a waveguide structure particle interacts with TM modes only. In the next paragraph we will discuss TM modes in a metamaterial-loaded waveguide.

MODE STRUCTURE IN A WAVEGUIDE LOADED WITH MTM

Metamaterials are generally anisotropic. It is very difficult to assemble an isotropic three-dimensional metamaterial. Experimentally we aim to have e and mu the same in the transverse directions. We will assume a waveguide to be aligned longitudinally with the z-axis.

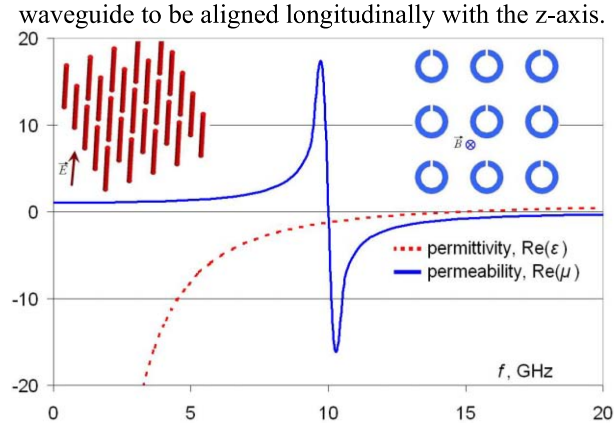

Figure 1: Wire array, split ring resonators. Frequency dependence of artificial permittivity and permeability.

A rectangular waveguide is chosen to have the same type of alignment as metamaterials. The size of the waveguide is *a* along *x* direction and *b* along *y* direction. We chose our metamaterial to have the following tensors for permittivity and permeability.

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix}, \quad \hat{\mu} = \begin{pmatrix} \mu_\perp & 0 & 0 \\ 0 & \mu_\perp & 0 \\ 0 & 0 & \mu_\parallel \end{pmatrix} \qquad (1)$$

$$\varepsilon(\omega)=1-\frac{\omega_p^2}{\omega^2+i\gamma\omega},\ \varepsilon_{\parallel}=1, \tag{2}$$

$$\mu_{eff}(\omega)=1-\frac{F\omega^2}{\omega^2-\omega_{res}^2+i\gamma\omega},\mu_{\parallel}=1, \tag{3}$$

Such dispersive behavior for and can be achieved by the split ring resonators (SRR) [10] and wire array [11] figure 1. Here ω_p, ω_{res} and γ are determined by the geometry of the metamaterial elements. The anisotropic properties are realized by the metamaterial design we plan to study experimentally [9], figure 2.

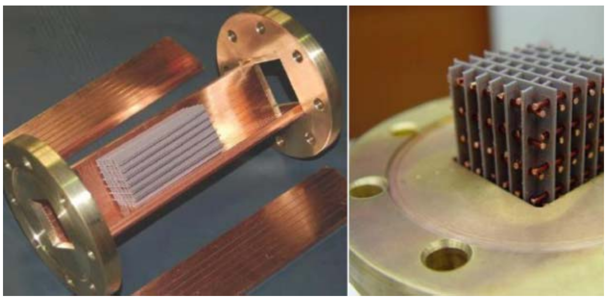

Figure 2: Waveguide loaded with anisotropic dispersive metamaterial.

We will consider the waveguide to be aligned along z-direction. We search for propagating solutions ($\exp(ik_z z)$) of Maxwell's equations in frequency domain using standard methods.

We obtain for the phase vector:

$$k_z^2=k_0^2\varepsilon_{\perp}\mu_{\perp}\left(1-\frac{\chi_x^2+\chi_y^2}{\varepsilon_{\parallel}\mu_{\perp}k_0^2}\right) \tag{4}$$

Here $k_0=\omega/c$, $\chi_x=\pi m/a$ and $\chi_y=\pi n/b$, *m, n* – mode indices and *a, b* – dimensions of the waveguide.

Anisotropic and dispersive material changes the dispersion of the waveguide modes significantly (figure 3). One major difference is existence of modes below cutoff frequency of the empty waveguide (termed non-magnetic band [9, 12]). Also we observe several regions with negative group velocity (negative slope).

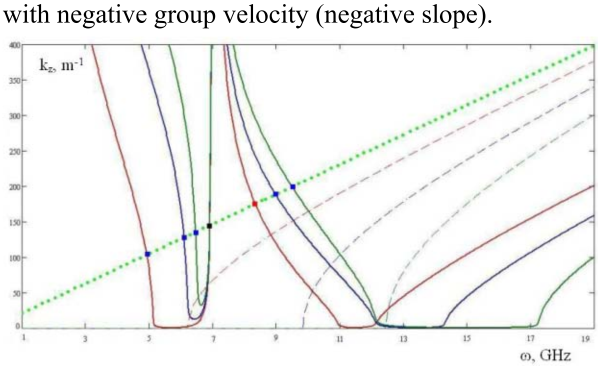

Figure 3: Dispersion of TM11 (red), TM21 and TM12 (blue, degenerate) and TM22 (green) modes. Solid lines correspond to LHM-loaded case, dashed – empty waveguide. Dotted line is particle dispersion. Intersection of particle dispersion with dispersion curves of the modes shows at which frequency any particular mode can be excited.

Fast particles (we consider electrons at speed v, close to c) can generate modes in metamaterial-loaded waveguide. To show this we plot the electron dispersion ($k_0=\omega/v$) together with dispersion of the modes. Points where the electron line and mode dispersion intersect indicate the frequencies and phase numbers of modes, which can be excited by a particle (figure 3).

WAKEFIELD GENERATION IN A WAVEGUIDE LOADED WITH MTM

The dispersion curve method does not give information as to which modes will absorb more energy from the particles. We performed a wakefield simulation in a waveguide cross section for a "pancake" beam of any transverse distribution [14]. We use a finite element method, which allows us to resolve a physical delta-function (figure 4). We simulate an off-centered beam to see the excitation of dipole modes.

The result of simulation is a spectrum of modes, E_x field measured on the side wall of the waveguide. We observe the each mode can be generated at two different frequencies. Since the particle is passing not through the center of the waveguide it generates TM_{21}, TM_{12}, TM_{22} and other dipole modes. Usually, for a waveguide loaded with a non-dispersive dielectric higher order modes absorb more energy from the particle. In this case due to dispersion of the media higher order modes absorb less energy.

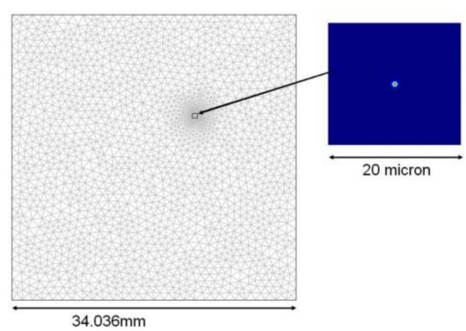

Figure 4: Irregular mesh in finite element method. Mesh is refined in the center to resolve a micron size off-centered beam with 1nC charge passing through the waveguide.

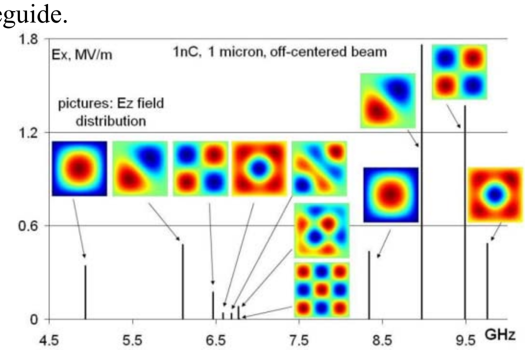

Figure 5: E_x, *MV/m* on the side wall of the waveguide, spectrum. Pictures show the field distribution at particular value of a parameter ω.

1-4244-0917-9/07/$25.00

WAKEFIELD GENERATION EXPERIMENT

Just recently we have got the first data of our wakefield generation in metamaterial loaded waveguides experiment. Approximately ¼ nC electron beam of Argonne Wakefield Accelerator was passing through the metamaterial-loaded waveguide. Electric field was measured using a pick up probes at different locations on the side wall of the waveguide with a fast scope figure 6.

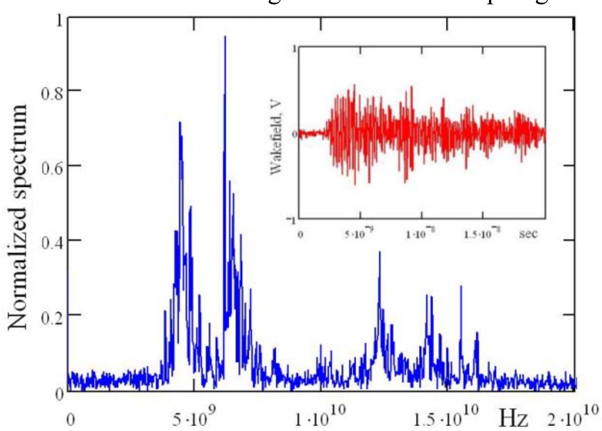

Figure 6: Wakefield and its spectrum, experimentally measured in a metamaterial-loaded waveguide.

The full analysis of the data is not yet done, but there are several important features in the spectrum. First of all there is a strong signal below cutoff frequency of the empty waveguide (6.228GHz). Also there is an excitation (weak) at around 10GHz. This is consistent with the cold tests of the structure.

SUMMARY

We discussed the interaction of a particle distribution with metamaterials. This is done using a uniform media approximation, where the metamaterial is substituted by an effective media it is supposed to mimic, having appropriate tensors of permittivity and permeability. The particular case of 2-axis crystal was studied. We used a method of dispersion curves to analyze particle interaction with the modes of metamaterial-loaded waveguide. This method is simple and provides frequencies and the modes, which can be excited by the particle, traveling through such system at speed *v*. However it does not tell which mode will absorb more energy from the particle. It depends on the transverse and longitudinal beam distribution and linearly scales with the total charge. A simulation approach is described that treats the problem of a beam propagating through the waveguide loaded with anisotropic and dispersive medium. The method also allows us to study various waveguide cross-sections and transverse beam distributions. We checked the simulation against known codes for dielectric loaded accelerators based on exact solutions [14]. Then we presented results for wakefield generation in the waveguide loaded with anisotropic and dispersive media. Finite element method makes it possible to simulate physically small (much smaller than the waveguide cross section) sources due to a possibility of refining mesh locally at the places of interest.

Waveguides loaded with anisotropic and dispersive media have various interesting regimes of *TM*-modes propagation and excitation. They can be of interest for particle detection. Metamaterial-loaded waveguides can be used for example as beam-position monitors and multi-threshold detectors [14].

We present the first experimental data of wakefield generation in metamaterial loaded waveguide. Several interesting features are pointed out, but the full analysis is yet to come.

The submitted paper has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357.

This work is also supported by the National Science Foundation grant # 0237162.

REFERENCES

[1] V. G. Veselago, Soviet Physics Uspekhi, 10, 509 (1968).
[2] J. Lu, T. M. Grzegorczyk, Y. Zhang, J. Pacheco, B. I. Wu, J. A. Kong, M. Chen Optics Express, 11, 723 (2003).
[3] Yu. O. Averkov and V. M. Yakovenko, Phys. Rev. B 72, 205110 (2005).
[4] R. Shelby, D. R. Smith and S. Schultz, Science, 292, 77 (2001).
[5] S. Antipov, W. Liu, J. Power and L. Spentzouris. “Left-Handed Metamaterials Studies and Their Application to Accelerator Physics” PAC05 proc.
[6] R. W. Ziolkovski IEEE Trans. On Antennas and Propagation, 51, 7, 2003.
[7] S. Antipov, W. Liu, J. Power and L. Spentzouris. Wakefield note at Argonne Wakefield Accelerator http://www.hep.anl.gov/awa/wfnotes/wf229.pdf.
[8] R. A. Shelby, D. R. Smith, S. C. Nemat-Nasser and S. Schultz, Appl. Phys. Lett., 78, 4 (2001).
[9] Double-negative metamaterial research for accelerator applications. S. Antipov, W. Liu, W.Gai, J. Power and L. Spentzouris. In press. Nucl. Instr. and Meth. A. NIMA-D-07-00227R1
[10] J. B. Pendry, A. J. Holden, D. J. Robbins and W. J. Stewart, IEEE Trans. Micr. Theory and Techniques , 47, 2075 (1999).
[11] J. B. Pendry, A. J. Holden, W. J. Stewart and I. Youngs Phys. Rev. Lett., 76, 4773 (1996).
[12] V. A. Podolskiy and Ev. E. Narimanov, Phys. Rev. B 71, 201101(R) (2005).
[13] A. L. Pokrovsky and A. L. Efros, Phys. Rev. Lett. 89, 093901 (2002)
[14] Metamaterial-loaded waveguides: dispersion analysis and simulations of wakefield generation. S. Antipov, W. Liu, W.Gai, J. Power and L. Spentzouris. Submitted. Jour. Appl. Phys. JR07-2247.

