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Double-negative metamaterial research for accelerator applications

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Abstract

Material properties are central to the design of particle accelerators. One area of advanced accelerator research is to investigate novel materials and structures and their potential use in extending capabilities of accelerator components. Within the past decade a new type of artificially constructed material having the unique property of simultaneously negative permittivity and permeability has been realized, and is under intense investigation, primarily by the optical physics and microwave engineering communities [C.M. Soukoulis, Science 315 (2007) 47; D.R. Smith, J.B. Pendry, M.C.K. Wiltshire, Science 305 (2004) 788; J.B. Pendry, A.J. Holden, W.J. Stewart, I. Youngs, Phys. Rev. Lett. 76 (1996) 4773]. Although they are typically constructed of arrays of discrete cells, as long as the condition that the wavelength of applied radiation is significantly greater than the cell dimensions is met, the material mimics a continuous medium and can be described with the bulk properties of permittivity, ε, and permeability, μ. When the permittivity and permeability are simultaneously negative in some frequency range, the metamaterial is called double negative (DNM) or left-handed (LHM) and has unusual properties, such as a negative index of refraction. An investigation of these materials in the context of accelerators is being carried out by IIT and the Argonne Wakefield Accelerator Facility [S. Antipov, W. Liu, W. Gai, J. Power, L. Spentzouris, AIP Conf. Proc. 877 (2006); S. Antipov, W. Liu, J. Power, L. Spentzouris, Design, Fabrication, and Testing of Left-Handed Metamaterial, Wakefield Notes at Argonne Wakefield Accelerator, ⟨http://www.hep.anl.gov/awa/wfnotes/wf229.pdf⟩]. Waveguides loaded with metamaterials are of interest because the DNM can change the dispersion relation of the waveguide significantly. For example, slow backward waves can be produced in a DNM-loaded waveguide without having corrugations. This article begins with a brief introduction of known design principles for realizing a DNM [J.B. Pendry, A.J. Holden, W.J. Stewart, I. Youngs, Phys. Rev. Lett. 76 (1996) 4773; D.R. Smith, et al., Phys. Rev. Lett. 84 (2000) 4184; J.B. Pendry, A.J. Holden, D.J. Robbins, W.J. Stewart, IEEE Trans. Microwave Theory Tech. 47 (1999) 2075], along with a description of the experimental verification of the basic DNM properties of our designs. We then present our waveguide analysis, starting with the case of a waveguide loaded with a truly continuous medium that is dispersive and anisotropic. We show that the dispersion relation of a waveguide with frequency regions of negative $\varepsilon(\omega)$ and negative $\mu(\omega)$ has several interesting frequency bands. While a DNM approximates a continuous medium, it is still made up of discrete elements. We discuss some implications of the discrete nature of the material for the behavior of a loaded waveguide, particularly at frequencies below the cutoff frequency of the waveguide. We conclude by describing our experimental program at present and in the near future. This includes testing the excitation of TM modes in a DNM loaded waveguide in the interesting frequency bands, both on the bench and from particle beam excitation.

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1. Introduction

In the present decade there has been intense interest in what are termed double-negative or left-handed metamaterials, because of their unusual response to applied radiation [1–3]. A metamaterial is a structure made of a repetitive array of unit cells. These are typically conducting strips and special loops with small gaps, called split-ring resonators, etched onto a substrate. When the physical dimensions of the cells are much smaller than the wavelength of applied radiation, the material can be

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described by the bulk properties permittivity, ε, and permeability, μ. If the permeability and permittivity are simultaneously negative in some frequency range, then a medium is termed double-negative, or left-handed. This combination of properties does not occur naturally. The electrodynamic behavior of Double-Negative Materials (DNM) was first investigated theoretically by Veselago [4]. Transmitted radiation has a phase velocity that counter-propagates with respect to the group velocity, and so obeys a left-handed rule for $\vec{E}$, $\vec{H}$, and $\vec{k}$, the electric, magnetic and phase vectors of the wave. The index of refraction, n, is negative in this circumstance. Pendry introduced principles for the design of DNMs in publications from 1996 [5] to 1999 [6]. This was followed by the construction of the first DNM by Smith et al. [7] in 2000.

Since the first realization of a DNM, there has been an explosion of research toward possible applications [1,3,8,9]. There is an intense research effort in the optical regime, stimulated by the possibility of ultrahigh-resolution imaging systems not offered with the current technology [1,3]. Due to the small cell size required in the optical range, development of the geometry and fabrication techniques is still an area of significant effort. In the microwave frequency range, achieving a DNM is less of a challenge, enabling a broad effort on microwave applications, such as the design of highly compact bandpass filters [8,9].

The behavior of materials has always played a central role in the design and construction of particle accelerators. An area of advanced accelerator research is to investigate novel methods, materials, or structures for their potential as high performance accelerator components, or for effectiveness in alleviating such problems as higher order mode excitation in accelerating structures. Notable work has been done at MIT on mode suppression through structure design, where a photonic band gap accelerating structure has been realized [10]. The MIT structure was a photonic crystal, a repetitive array of rods creating a frequency gap in which radiation cannot propagate through the structure. A defect in the array enables trapping of the accelerating mode. A group at the University of Texas [11] is working on surface wave accelerating SiC structures based on negative permittivity. Research efforts such as these use special geometries and materials to customize the response of a structure to electromagnetic excitation.

We report here on research being done at the Argonne Wakefield Accelerator facility [12–14]; specifically, an investigation of the use of DNM to control the dispersion relation in a loaded waveguide. Analysis done for a continuous anisotropic medium having the same permittivity and permeability tensors as a DNM shows synchronism between relativistic particles and the fundamental (backward) accelerating mode. It also shows a dipole mode below the cutoff frequency for the waveguide. Simulations have enabled a detailed study of the higher order modes of such a structure, assuming a continuous medium. Investigation is underway on how the discrete nature of the metamaterial affects these results. We have found that mode coupling in the structure depends on the relative placement of the split-ring resonators (SRRs) and the wire grids, as well as on the overall symmetry. Dipole mode suppression may depend on the discrete nature of the material in conjunction with being below the cutoff frequency of the waveguide. This is discussed, drawing on analysis of a waveguide loaded with a wire grid in what is termed the non-magnetic regime [15,16].

A description of our metamaterial designs, some discussion of the principles of DNMs, and some early experimental verification of the properties of our DNM are presented in Section 2. Section 3 has two parts, the first part gives analytic and simulation results for a waveguide loaded with a continuous, dispersive, anisotropic medium. The continuous medium is an approximation to our discrete-element structures. Our continuous media studies illuminate how the dispersion function of the loaded waveguide depends on the permittivity and permeability of the DNM design. The second part of Section 3 is devoted to discrete DNM structures. A discussion of potential dipole mode suppression is included, a feature that depends on the discrete nature of metamaterials. Section 5 concludes with a summary and the current status of our research.

2. Metamaterial design

Our double-negative metamaterial design follows the principles of the other earlier realized DNM designs [7,17]. It consists of either a wire array or an array of capacitively loaded strips for permittivity (ε) control, and an array of split-ring resonators for permeability (μ) control. These two arrays are put together as one continuous array of conducting strips and SRRs for simultaneous control of the permittivity and permeability. In order to obtain a double-negative metamaterial, there must be some frequency region in which both the permittivity and permeability are negative. If only one of these parameters is negative, electromagnetic waves will not be transmitted, the amplitude of the radiation will decay within the material. The permittivity and permeability must be simultaneously positive or simultaneously negative in order to have propagation through a material. Our first metamaterial design was done on a series of printed circuit boards, and is shown in Fig. 1. The middle of the three circuit boards of Fig. 1 has the capacitively loaded wire strips alone, the right-most of the three boards has only SRRs, and the left-most of the three boards has split-ring resonators and capacitively loaded strips combined.

2.1. Negative permittivity

Negative permittivity, ε, naturally occurs in plasmas at frequencies below the plasma frequency ω_p, and for conduction band electrons in metals at optical frequencies. A wire array can also exhibit plasma-like behavior in the