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Features of surface modes in metamaterial layers

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Abstract

In this paper, we present a study of the waveguiding properties of metamaterial layers. We pay particular attention to peculiar features that have not yet been given sufficient consideration in previous publications, with an emphasis on the physical interpretation of these results. We attempt to follow the transition of waves guided by a solitary "metamaterial–vacuum" boundary (the so-called true surface wave—TSW) to modes guided by the metamaterial layer. We considered the way TSW of different types (forward, backward and degenerated) transform to the layer modes and examined the features arising in the dispersion curves. For example, "pulling" of the dispersion curve into the frequency region where TSWs do not exist separately, presence of the bend for all modes produced by backward TSWs, existence of the waves with complex conjugate propagation constants, etc.

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1. Introduction

In this paper, we analyze peculiar waveguiding properties of metamaterial layers. The metamaterials in this work are defined as artificial media with electrodynamic characteristics that are unusual for natural dielectrics and magnetics, namely, the separate components of tensors of dielectric and magnetic permeabilities ($\hat{\varepsilon}$ and $\hat{\mu}$, respectively) simultaneously take on negative values in a certain frequency range. The vectors of the electric (**E**) and magnetic (**H**) fields in a plane wave propagating through such isotropic media form not a right-handed, but a left-handed triplet with the wave vector (**k**), i.e., homogeneous plane waves are backward waves (the phase velocity and the Poynting vector are directed against each other). The creation of these metamaterials was first reported by Smith et al. [1,2], where the authors referred to the theoretical results obtained by Pendry et al. [3,4].[1]

A most comprehensive theoretical description of electrodynamics properties of medium with negative ε and μ values has been made by Veselago [7]. However, some intrinsic properties of this medium have been discussed in the beginning of the XX century. For example, the possibility of opposite directionality of the phase velocity and Poynting vector has been considered by Lamb [8]. First detail discussion on negative refraction can be found in Mandelshtam's lectures [9].

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[1] It should be noted, that theoretical proposals relating to the possibility of producing media with negative ε were well known before (see e.g. [5,6]).

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The practical realization of medium with negative ε and μ resulted in a deluge of publications, where the creation of metamaterials in different frequency ranges (microwave (see e.g. [10,11]) and terahertz (see e.g. [12,13]) ranges and further, up to optical wavelengths (see e.g. [14])) was reported, with various proposals regarding their practical applications (perfect lens [15], cloaking [16], etc.). Such media are of considerable interest for the creation of various waveguiding devices, resonators, slow-wave systems, and also, can be applied for the miniaturization of the guiding structures [17,18].

The dispersion properties of metamaterial layers have been discussed previously at sufficient length [19–25], and arguably most detailed classification of layer modes given in the paper by Vukovich et al. [21]. However, many relevant issues relating to the connection of waveguide modes of a layer with a TSW at the interface boundaries that produce them, which we believe to be rather interesting, have not yet been sufficiently discussed. This will be the main focus of this paper. The presented results are of interest in connection with the discussion of the possibility of realization of the perfect lens.

We will closely trace the transition from surface waves directed by one interface boundary between a metamaterial and a usual medium, to the surface modes of a metamaterial layer having two such boundaries. In this case, the layer modes are considered to be a result of the interaction of two surface waves confined by different boundaries. As the layer thickness decreases, this interaction becomes increasingly stronger and significantly influences the dispersion properties of the modes.

If the characteristic distances between resonant elements in a metamaterial are short compared with the length of a propagating wave, one can pass over to the continuous-medium limit and introduce the notions of tensors of dielectric and magnetic permeabilities, which, in the absence of "gyrotropic" elements, have a diagonal form in the main axes. To be specific, in what follows, we will consider "single-axis crystals", in which the symmetry axis is oriented along the x coordinate:

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} = \varepsilon_{\perp} & 0 & 0 \\ 0 & \varepsilon_{yy} = \varepsilon_{||} & 0 \\ 0 & 0 & \varepsilon_{zz} = \varepsilon_{||} \end{pmatrix},$$

$$\hat{\mu} = \begin{pmatrix} \mu_{xx} = \mu_{\perp} & 0 & 0 \\ 0 & \mu_{yy} = \mu_{||} & 0 \\ 0 & 0 & \mu_{zz} = \mu_{||} \end{pmatrix}. \qquad (1)$$

When losses are neglected, the frequency dependences of the components of the tensors $\hat{\varepsilon}$ and $\hat{\mu}$ in the metamaterials made of resonant elements have a following character:

$$\begin{aligned} \varepsilon_{\perp,||} &= 1 - \frac{\omega_{p\perp,||}^2}{\omega^2 - \omega_{\varepsilon\perp,||}^2}, \\ \mu_{\perp,||} &= 1 - \frac{\omega_{m\perp,||}^2}{\omega^2 - \omega_{\mu\perp,||}^2}, \end{aligned} \qquad (2)$$

where ω is the frequency of the process, and $\omega_{p\perp,||}$, $\omega_{\varepsilon\perp,||}$, $\omega_{m\perp,||}$, and $\omega_{\mu\perp,||}$ are the parameters determined by the internal structure of the metamaterial (namely, geometry of resonant elements and filling factor).

2. Isolated boundary of the metamaterial–vacuum interface

It is well known [26–30] that a boundary plane of a metamaterial–vacuum interface is capable of maintaining true surface waves (TSWs) "pressed" to this boundary on both sides. The wave responsible for the presence of waveguide modes in conventional dielectric layers (see, e.g. [31]) is a surface wave caused by the phenomenon of total internal reflection (an "untrue" surface wave, in our terminology): it is pressed to the boundary on only one side and oscillates at the other side. In this work, we will focus on the analysis of waveguide modes formed by TSWs. Classical examples of such waves are the waves confined by the boundary of the interface between vacuum and a plasma, with $\varepsilon < -1$ [32,33]. For such waves, the energy flux density coincides with the direction of propagation (at the phase velocity) in free space, but their direction is opposite in the neighboring plasma. However, the total energy flux in a given TSW is always aligned with the phase velocity, and hence, the waves themselves are forward-traveling. By replacing the plasma with a metamaterial, in which both the dielectric and magnetic permeabilities are simultaneously negative, the possibilities of TSW realization become wider, and we can create backward surface waves. Now, we will briefly review the information about TSW [30] that is necessary for understanding the following discussion.

Let the interface boundary coincide with the $x = 0$ plane, i.e., values where $x > 0$ correspond to the metamaterial, and values where $x < 0$ correspond to the electrodynamic vacuum. The dispersion equations are