Propagation of Electromagnetic Waves in Cylindrical Three-layers Waveguide with Metamaterial Layer

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Abstract— We present results of modeling of waveguides modes propagation coefficients in cylindrical tree-layer waveguide in this work. Intermediate layer is LHM (Left-Handed-Medium) metamaterial with negative index of refraction. The outer and inner layers are conventional materials with positive index of refraction RHM (Right-Handed-Medium). Our results indicate that in such waveguides exist complex waves and waves with a significant slowdown of phase.

1. INTRODUCTION

V. G. Veselago [1] predicted theoretically the originality of physical phenomenon's by reflection and refraction of electromagnetic waves on borders section "right" and "left" mediums. This is provided the impetus for modeling electromagnetic processes in different transmission lines [2–6]. The purpose of this work is modeling of wave processes in cylindrical waveguide that contained three layers with "right" and "left" mediums.

2. FORMULATION OF THE PROBLEM

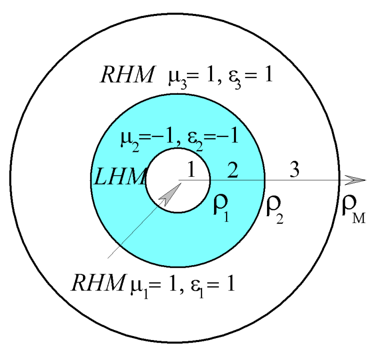

Figure 1: Three-layer waveguide.

On Figure 1 are shown cross-section three-layer waveguide with ideal conductive outer shield and geometrical characteristics of the layer's. We used cylindrical coordinate system r, ϕ, z_0. The waves spread along coordinate z, directed into plane's drawing. The dependence of components fields on azimuth and longitudinal coordinates is selected in the form: $\exp(in\phi + i\beta z)$, where n — azimuth number, β — propagation constant. We study the behavior of the propagation constants of the guided modes. The chose of structure is specified by simplicity of dispersion equation for calculation of propagation constants of eigen waves. The dispersion equation comes from realizing boundary conditions for tangent components of EM fields on borders section medium. The propagation constant are normalized on wave number of free space: $\Gamma = \beta/k_0 = c/v$, where v — phase velocity of wave in waveguide. The complex character $\Gamma = \mathrm{Re}(\Gamma) + i\mathrm{Im}(\Gamma)$ means the rise of complex waves. Imaginary character of propagation constant means the absence of wave process. The radii of the layers and the longitudinal coordinate is normalized on the wave number of free space: $\rho = k_0 r$, $z = k_0 z_0$, $k_0 = \omega/c$, where c is speed of light in free space. The purpose of modeling is the explanation of the influence of the thickness of the central dielectric and its dielectric constant on the propagation constants of the guided modes.

3. THE RESULTS OF NUMERUCAL EXPERIMENTS

Figure 2 shows the dependences of the propagation constants of the waves having a field variation in azimuth (the first subscript at the bottom in the name of the wave) on the radius ρ_2. The names of waves are specified in accordance with accepted literature recommendation [10]. In the absence of LHM material ($\rho_1 = \rho_2$) results are well-known in the literature. On Figure 2 axis $\mathrm{Re}\,(\Gamma)$ and $\mathrm{Im}\,(\Gamma)$ are combined (superposed). In this case, we see the place of the "cut-off" regions and wave propagation regions.

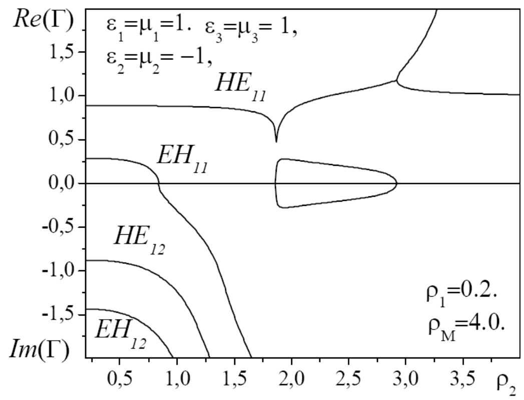

Figure 2: The radius of the first layer is 0.2. Dependences of the propagation constants on the outer radius of the second layer of waveguide.

The analysis of results shows the existence of two propagating modes (HE_{11}, EH_{11}) and two "cut off" modes (HE_{12}, EH_{12}) having an imaginary value of Γ. Increase ρ_2 makes "cut off" mode the mode EH_{11}. This fact is new. It can be explained from position of partial waves. In the LHM medium the direction of propagation ray becomes opposite. With increase of LHM layer thickness grows ray's way in opposite direction and Γ aspires to 0. An another phenomenon observed at the growth of the radius ρ_2. The bifurcation is observed in multilayer waveguide with increasing thickness of the second layer. The wave HE_{11} is divided into two waves. The further increase of the thickness of the layer leads to a significant increase in the propagation constant ($\Gamma \to \infty$).

Figure 3 shows the dependences of the propagation constants on the permeability of the first layer ε_1 at fixed values of the radiuses ($\rho_1 = 0.2$, $\rho_2 = 0.5$).

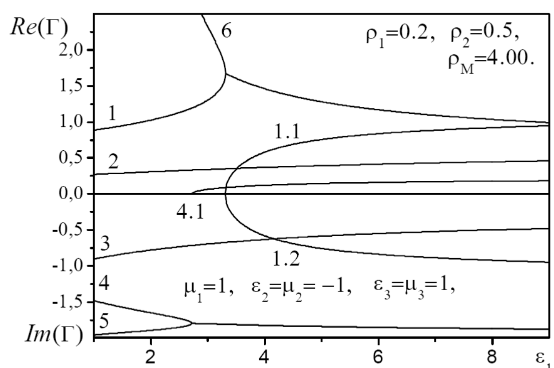

Figure 3: Three-layer waveguide. Curved 1 — HE_{11} mode, 2 — EH_{11}, 3 — HE_{12}, 4 — EH_{12}, 5 — HE_{12}.

The increase in permeability leads to an increase of the propagation constant of the mode HE_{11} (curve 1). There is a mode with very low phase velocity in the waveguide (curve 6). This is an unusual result. The bifurcation is occurs for these modes. In the spectrum there are two complex conjugate wave modes. They have anomalous behavior. For other modes, there are many different effects. The appearance of waves with a significant slowing of the phase velocity and abnormal behavior is associated with the existence of a layer of LHM.

4. CONCLUSION

We are considered various options for modifying the parameters of the multilayer waveguide at the modeling process [7–9]. The qualitative picture of the propagation constant of the waves does not change. We can talk about the features of propagation of electromagnetic waves in a waveguide with LHM and RHM layers:

1. In the waveguide can be implemented as a wave process, and the "cut off" mode process at the change of the second layer radius.

2. The emergence of LHM layer in the waveguide leads to a strong deceleration of phase velocity for some modes.

3. In the waveguide are observed complex conjugate waves and anomalous behavior of the propagation constants.

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