PROPERTIES OF ELECTROMAGNETIC WAVES THAT PROPAGATE ALONG THE LEFT-HAND MATERIAL SLAB

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This report is devoted to the investigation of the dispersion and the spatial distribution of the electromagnetic field of the surface type waves that propagate along the planar waveguide structure. This structure consists of the left-handed material slab, bounded by the semi-infinite regions of ordinary dielectric with constant permittivity and permeability. The wave considered propagates along the interface between left and right handed materials. The obtained results can be useful for the future image processing applications.

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1. INTRODUCTION

In recent years the new artificial materials have been created with both negative effective permittivity and effective permeability over some frequency ranges [1]. The materials of such type (with negative refractive index) are often called left-handed materials, because Poynting vector in such media is opposite to the wavevector. The idea of a negative refractive index opens up the new conceptual frontiers in science and technology. Waves, that propagates in such materials possesses a lot of interesting properties [2]. Devices, based on the left handed materials are the matters of intensive theoretical and experimental studies. Such structures have a high potential for the future image processing applications due to unprecendented flexibility in electromagnetic waves manipulating and producing new functionalities. One of such intriguing example is the concept of a perfect lens that enables imaging with sub-wavelength image resolution [2].

The resolution of optical systems equals the wavelength of light and does not allow resolve features smaller than this size. The reason of this consists in the fact that the high spatial harmonics that describe the sub-wavelength details of image are evanescent modes. Such modes do not propagate and decay exponentially on a wavelength distance from the object. So, the transmission of evanescent modes is an issue of the day for the modern optics, data storage, optical lithography, imaging of living objects and so on.

The sub-wavelength imaging becomes possible due to the resonant excitation of the surface plasmons on the surfaces of left-handed materials by evanescent waves existing near an object [3]. These surface plasmons subsequently excite the evanescent waves reproducing the object's near fields in the image plane. In this way the super-resolution is achieved by the amplification of near fields by the surface plasmon resonances.

The surface plasmon/polariton modes existing near the boundary of such a left-handed medium with an ordinary right-handed medium were investigated in this work.

2. PROBLEM FORMULATION

It was considered the propagation of the electromagnetic wave in the planar waveguide structure that consists of left-handed material slab with thickness Δ. This material is characterized by the permittivity and the permeability that depends on the wave frequency. The left-media slab is surrounded by the ordinary dielectric with constant permittivity ε_d and permeability μ_d. The diagram of considered geometry is shown in the Fig. 1.

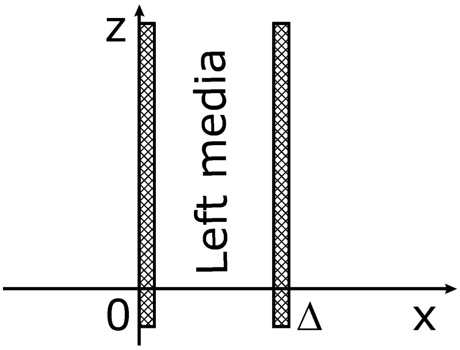

Fig. 1. The diagram of the geometry of the considered planar waveguide structure

The left-handed material slab is characterized by the experimentally obtained expression for the effective permittivity, which is usually used in the majority of theoretical studies [4]:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}, \tag{1}$$

where ω_p is plasma frequency which value is about of some *GHz* for the most artificially constructed left-handed materials [4]. The effective permeability of such materials can be written as:

$$\mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2}, \tag{2}$$

where ω_0 is the characteristic frequency of left-handed materials with the value about of some *GHz*. In further study it was considered the left-handed materials with $\omega_p = 10$ GHz and $\omega_0 = 4$ GHz and the parameter $F = 0.56$ [5].

Let us consider the surface waves that propagate along the interface between the left and right handed materials. It was assumed that the dependence of the wave components on time t and coordinate z can be expressed in the following form:

$$\propto \exp[i(k_z z - \omega t)]. \tag{3}$$

For the considered waveguide structure the Maxwell's equations that govern the wave propagation split into two independent subsystems. One of them describes the waves of p- polarization and another – the wave of s- polarization.

The wave of p- polarization possesses the dispersion relations in the following form:

$$\varepsilon(\omega)h = -\varepsilon_d \kappa \coth(\Delta\kappa/2)\,, \qquad (4)$$

$$\varepsilon(\omega)h = -\varepsilon_d \kappa \tanh(\Delta\kappa/2)\,, \qquad (5)$$

where $\kappa = \sqrt{\mathrm{k}_z^2 - \varepsilon(\omega)\mu(\omega)k^2}$, $h = \sqrt{\mathrm{k}_z^2 - \varepsilon_d \mu_d k^2}$, $k = \omega/c$, were c is the speed of light in vacuum.

In the region of left-handed material the wave field components, normalized on the $H_y(0)$, can be written as:

$$\begin{cases} H_y(x) &= C_1 e^{\kappa x} + C_2 e^{-\kappa x}, \\ E_x(x) &= \dfrac{k_z}{k\varepsilon(\omega)}\left(C_1 e^{\kappa x} + C_2 e^{-\kappa x}\right), \\ E_z(x) &= \dfrac{i}{k\varepsilon(\omega)}\left(C_1 \kappa e^{\kappa x} - C_2 \kappa e^{-\kappa x}\right), \end{cases} \qquad (6)$$

where C_1 and C_2 – are the wave field constants.

The wave field components, normalized on the $H_y(0)$ component in the region of left-handed dielectric possess the form:

$$\begin{cases} H_y(x) &= e^{hx}, \\ E_x(x) &= \dfrac{k_z e^{hx}}{k\varepsilon_d}\,, \\ E_z(x) &= \dfrac{ihe^{hx}}{k\varepsilon_d}. \end{cases} \qquad (7)$$

In the region of the ordinary dielectric the wave field components, normalized on the $H_y(0)$, can be written as:

$$\begin{cases} H_y(x) &= Be^{-hx}, \\ E_x(x) &= B\dfrac{k_z e^{-hx}}{k\varepsilon_d}, \\ E_z(x) &= -iB\dfrac{he^{-hx}}{k\varepsilon_d}, \end{cases} \qquad (8)$$

where B is wave field constant. These wave field constants are of the following form:

$$\begin{cases} B &= -\dfrac{2h\varepsilon(\omega)e^{\Delta(h+\kappa)}}{(e^{2\Delta\kappa}+1)h\varepsilon(\omega) + (e^{2\Delta\kappa}-1)\kappa\varepsilon_d}, \\ C_1 &= \dfrac{h\varepsilon(\omega)(h\varepsilon(\omega) - \kappa\varepsilon_d)}{\kappa\varepsilon_d((e^{2\Delta\kappa}+1)h\varepsilon(\omega) + (e^{2\Delta\kappa}-1)\kappa\varepsilon_d)}, \\ C_2 &= -\dfrac{h\varepsilon(\omega)(h\varepsilon(\omega) + \kappa\varepsilon_d)e^{2\Delta\kappa}}{\kappa\varepsilon_d((e^{2\Delta\kappa}+1)h\varepsilon(\omega) + (e^{2\Delta\kappa}-1)\kappa\varepsilon_d)}. \end{cases} \qquad (9)$$

Similarly, the wave of s- polarization possesses the following dispersion relations:

$$\mu(\omega)h = -\mu_d \kappa \coth(\Delta\kappa/2)\,, \qquad (10)$$

$$\mu(\omega)h = -\mu_d \kappa \tanh(\Delta\kappa/2)\,. \qquad (11)$$

In the region of the left-handed material the wave field components, normalized on the $E_y(0)$ component, can be written as:

$$\begin{cases} E_y(x) &= C_1 e^{\kappa x} + C_2 e^{-\kappa x}, \\ H_x(x) &= -\dfrac{k_z}{k\mu(\omega)}\left(C_1 e^{\kappa x} + C_2 e^{-\kappa x}\right), \\ H_z(x) &= -\dfrac{i}{k\mu(\omega)}\left(C_1 e^{\kappa x} - C_2 e^{-\kappa x}\right), \end{cases} \qquad (12)$$

where C_1 and C_2 – are the wave field constants.

The wave field components, normalized on the $E_y(0)$ component, in the region of left-handed dielectric can be written as:

$$\begin{cases} E_y(x) &= e^{hx}, \\ H_x(x) &= \dfrac{k_z e^{hx}}{k\mu_d}, \\ H_z(x) &= -\dfrac{ihe^{hx}}{k\mu_d}. \end{cases} \qquad (13)$$

In the region of ordinary dielectric the wave field components, normalized on the $E_y(0)$, can be written as:

$$\begin{cases} E_y(x) &= Be^{-hx}, \\ H_x(x) &= -B\dfrac{k_z e^{-hx}}{k\mu_d}, \\ H_z(x) &= iB\dfrac{he^{-hx}}{k\mu_d}. \end{cases} \qquad (14)$$

where B is the wave field constant. The wave field constants for the considered wave are of the following form:

$$\begin{cases} B &= -\dfrac{2h\mu(\omega)e^{\Delta(h+\kappa)}}{(e^{2\Delta\kappa}+1)h\mu(\omega) + (e^{2\Delta\kappa}-1)\kappa\mu_d}, \\ C_1 &= \dfrac{h\mu(\omega)(h\mu(\omega) - \kappa\mu_d)}{\kappa\mu_d((e^{2\Delta\kappa}+1)h\mu(\omega) + (e^{2\Delta\kappa}-1)\kappa\mu_d)}, \\ C_2 &= -\dfrac{h\mu(\omega)(h\mu(\omega) + \kappa\mu_d)e^{2\Delta\kappa}}{\kappa\mu_d((e^{2\Delta\kappa}+1)h\mu(\omega) + (e^{2\Delta\kappa}-1)\kappa\mu_d)}. \end{cases} \qquad (15)$$

3. MAIN RESULTS

The results of the numerical calculations of the dispersion properties of the waves of both polarizations for rather thin left-handed dielectric slab are shown in Fig.2. The investigated equations (4, 5) and (10, 11) possesses six solutions. Curves marked by the numbers 1, 4, 6 correspond to waves with p- polarization. Curves marked by the numbers 2, 3, 5 correspond to waves with s- polarization. For the chosen parameters the slab of artificial material demonstrates the left-handed properties in the region where $1 < \mu < 1.5$. In another region it demonstrates the plasma-like behaviour ($\varepsilon(\omega) < 0$ and

$\mu(\omega) > 0$). The line (a) corresponds to $x = \sqrt{\varepsilon_d}\,\omega / c$, the line (c) corresponds to $\mu = 1$ and the lines (b) – to the $x = \sqrt{\varepsilon(\omega)\mu(\omega)}\,\omega / c$.

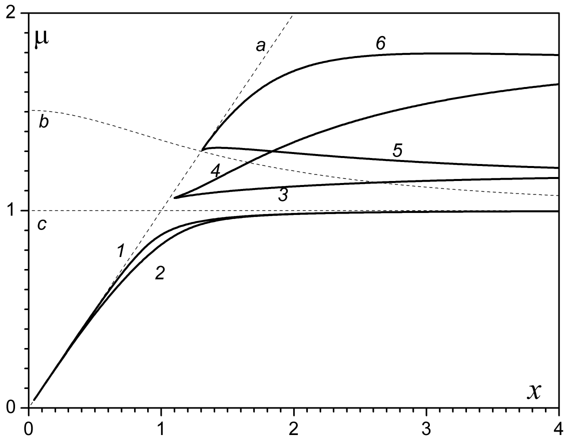

Fig. 2. The dependence of the normalized frequency $\mu = \omega / \omega_0$ on the dimensionless wavenumber $x = k_z c / \omega_0$ for the left-handed material slab thickness $\omega_0 \Delta / c = 0.6$

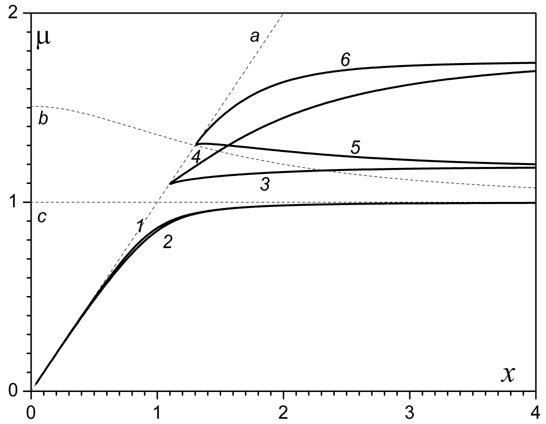

Fig. 3. The dependence of the normalized frequency $\mu = \omega / \omega_0$ on the dimensionless wavenumber $x = k_z c / \omega_0$ for the left-handed material slab thickness $\omega_0 \Delta / c = 0.9$

In the region above the curve (b) and right the curve (a) and below the curve (c) and right the curve (a) the investigated waves are of a pure surface type [6]. In the region above the curve (c) and below the curve (b) where the artificial material demonstrates the left-handed behaviour the analyzed waves possess some characteristics of the volume wave.

As it is shown on the Fig.3 the increase of left-handed material slab thickness leads to closing of the (1) and (2), (3) and (5), (4) and (6) curves.

CONCLUSIONS

In this report it was studied the specific features of the wave propagation in planar wave guide structure with left-handed material. It was investigated the dispersion properties and the wave field spatial structure for rather thick and rather thin left-handed material slabs. It was determined the dispersion characteristics as of the pure surface waves, as also the volume ones. The results obtained can be useful for the future image processing applications.

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СВОЙСТВА ЭЛЕКТРОМАГНИТНЫХ ВОЛН, РАСПРОСТРАНЯЮЩИХСЯ ВДОЛЬ СЛОЯ ЛЕВОЙ СРЕДЫ

Н.А. Азаренков, Ю.А. Акимов, В.К. Галайдыч, В.П. Олефир, А.Е. Споров

Исследуются дисперсионные свойства и пространственное распределение электромагнитного поля волны, распространяющейся в плоской волноводной структуре. Рассматриваемая структура состоит из слоя левой плазмоподобной среды, размещенной в диэлектрике с постоянной диэлектрической и магнитной проницаемостями. Исследуемые волны распространяются вдоль границы раздела левая среда – обычный диэлектрик. Полученные результаты могут быть использованы в системах передачи информации, обработке изображений и т.п.

ВЛАСТОВОСТІ ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ, ЩО РОЗПОВСЮДЖУЮТЬСЯ ВЗДОВЖ ШАРУ ЛІВОГО СЕРЕДОВИЩА

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Досліджуються дисперсійні властивості та просторовий розподіл електромагнітного поля хвилі, що поширюється в пласкій хвилеводній структурі. Структура, що розглядається, складається з шару лівого плазмоподібного середовища, що знаходиться в діелектрику зі сталими значеннями діелектричної та магнітної проникностями. Хвилі, що досліджуються, поширюються уздовж межі розподілу ліве середовище –діелектрик. Отримані результати можуть бути використані у системах передачі інформації, обробці зображень, та ін.