ELECTROMAGNETIC WAVES IN LEFT-HAND MATERIAL SLAB THAT BOUNDED BY MEDIA WITH DIFFERENT PERMITTIVITY

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The peculiar properties of surface type electromagnetic waves that propagate along the planar waveguide structure with left handed material bounded by conventional dielectric regions with different permittivity were studied in this work. It was shown that difference in dielectric's permittivity essentially influences on the dispersion properties and radial wave field structure of the waves considered. The results obtained can be useful in future biophysical and image processing applications and others.
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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 are often called left-handed materials (LHM). At first the LHM were composites, containing the periodic metallic inclusions of certain forms. Nowadays it has been obtained that artificial crystals of pirovskite class demonstrate left-handed properties [2].

The existence of left-handed materials opens up the new research fields in modern science and technology. Devices, based on the waves that propagate in the left handed materials are the matters of intensive theoretical and experimental studies [3]. The situation, when a LHM slab divides two dielectrics with different permittivity rather then equal ones, is more frequent in the possible applications.

The aim of this work is to investigate the specific features of the electromagnetic waves that propagate along the interfaces of a left-handed planar slab that bounded by the conventional right-handed media with different permittivity.

2. TASK SETTING

The considered electromagnetic wave propagates along the planar waveguide structure that is made of left handed material slab with thickness Δ. This material is characterized by effective permittivity $\varepsilon(\omega)$ and permeability $\mu(\omega)$ that depend on the wave frequency and commonly expressed with the help of experimentally obtained expressions [4]:

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

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

here ω_p is plasma frequency, ω_0 is the characteristic frequency of LHM. In further study it was considered LHM with $\omega_p = 10$ *GHz* and $\omega_0 = 4$ *GHz* and parameter $F = 0.56$ [5].

This left-media slab on both sides is bounded by semi-bounded conventional dielectrics with different constant permittivity and permeability. Dielectric with ε_1 and μ_1 is located at the left side of LHM slab and dielectric with ε_2 and μ_2 is located at the right side.

Let's consider electromagnetic wave that propagates along the interface between left and right handed materials. It was assumed that wave disturbance tends to zero far away from LHM and the dependence of the wave components on time t and coordinate and z is expressed the following form:

$$E, H \propto E(x), H(x)\exp[i(k_z z - \omega t)], \quad (3)$$

here x is coordinate rectangular to the wave propagation direction and to the LHM slab.

In this case the system of Maxwell equations split on two subsystems. One of them described the waves of E-type and another – wave of H-type.

The wave of E-type possesses the dispersion relation in the following form:

$$\frac{h_1 h_2 \varepsilon(\omega)^2 + \varepsilon_1 \varepsilon_2 \kappa^2}{\varepsilon(\omega)\,\kappa\,(h_2\varepsilon_1 + h_1\varepsilon_2)} \tanh(\kappa\,\Delta) = 0, \quad (4)$$

here $h_1 = \sqrt{k_3^2 - \varepsilon_1\mu_1 k^2}$, $h_2 = \sqrt{k_3^2 - \varepsilon_2\mu_2 k^2}$, $\kappa = \sqrt{k_3^2 - \varepsilon(\omega)\mu(\omega)k^2}$, $k = \omega / c$, 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:

$$H_y(x) = C_1 e^{\kappa x} + C_2 e^{-\kappa x},$$
$$E_x(x) = k_3\left(C_1 e^{\kappa x} + C_2 e^{-\kappa x}\right)/\left(k\,\varepsilon(\omega)\right), \quad (5)$$
$$E_z(x) = i\kappa\left(C_1 e^{\kappa x} - C_2 e^{-\kappa x}\right)/\left(k\,\varepsilon(\omega)\right),$$

here C_1 and C_2 – are wave field constants.

Wave field components, normalized on the $H_y(0)$, in the left dielectric region possess the form:

$$H_y(x) = e^{h_1 x},$$
$$E_x(x) = k_3 e^{h_1 x}/\left(k\,\varepsilon_1\right), \quad (6)$$
$$E_z(x) = i h_1 e^{h_1 x}/\left(k\,\varepsilon_1\right).$$

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

$$H_y(x) = Be^{-h_2 x},$$
$$E_x(x) = Bk_3 e^{-h_2 x}/(k\ \varepsilon_2), \qquad (7)$$
$$E_z(x) = -i\ B\ h_2 e^{-h_2 x}/(k\ \varepsilon_2),$$

here B is wave field constant. Such constants are of the following form:

$$B = -2\ h_1\ \varepsilon_2\ \varepsilon(\omega) e^{(h_2+\kappa)\Delta}/(\varepsilon_1 \Psi),$$
$$C_1 = h_1\ \varepsilon(\omega)\ (h_2\varepsilon(\omega) - \varepsilon_2\kappa)/(\varepsilon_1\ \kappa\ \Psi), \qquad (8)$$
$$C_2 = -h_1\ \varepsilon(\omega)\ (h_2\varepsilon(\omega) + \varepsilon_2\kappa) e^{2\kappa\Delta}/(\varepsilon_1\ \kappa\ \Psi),$$

here $\Psi = (e^{2\kappa\Delta}+1)\ \varepsilon(\omega)\ h_2 + (e^{2\kappa\Delta}-1)\ \varepsilon_2\ \kappa$.

Similarly wave of H-type possesses the dispersion relation in the following form:

$$\frac{h_1 h_2 \mu(\omega)^2 + \mu_1\mu_2\kappa^2}{\mu(\omega)\,\kappa\,(h_2\mu_1 + h_1\mu_2)} \tanh(\kappa\ \Delta) = 0\ , \qquad (9)$$

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

$$E_y(x) = C_1 e^{\kappa x} + C_2 e^{-\kappa x},$$
$$H_x(x) = -k_3 (C_1 e^{\kappa x} + C_2 e^{-\kappa x})/(k\ \mu(\omega)), \qquad (10)$$
$$H_z(x) = -i\kappa (C_1 e^{\kappa x} - C_2 e^{-\kappa x})/(k\ \mu(\omega)),$$

here C_1 and C_2 – are wave field constants.

Wave field components, normalized on the $E_y(0)$, in the left dielectric region:

$$E_y(x) = e^{h_1 x},$$
$$H_x(x) = -k_3 e^{h_1 x}/(k\ \mu_1), \qquad (11)$$
$$H_z(x) = -ih_1 e^{h_1 x}/(k\ \mu_1),$$

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

$$E_y(x) = Be^{-h_2 x},$$
$$H_x(x) = -Bk_3 e^{-h_2 x}/(k\ \mu_2), \qquad (12)$$
$$H_z(x) = i\ B\ h_2 e^{-h_2 x}/(k\ \mu_2),$$

here B is wave field constant. Such constants are of a following form:

$$B = -2\ h_1\ \mu_2\ \mu(\omega) e^{(h_2+\kappa)\Delta}/(\mu_1 \Psi),$$
$$C_1 = h_1\ \mu(\omega)\ (h_2\mu(\omega) - \mu_2\kappa)/(\mu_1\ \kappa\ \Psi), \qquad (13)$$
$$C_2 = -h_1\ \mu(\omega)\ (h_2\mu(\omega) + \mu_2\kappa) e^{2\kappa\Delta}/(\mu_1\ \kappa\ \Psi),$$

here $\Psi = (e^{2\kappa\Delta}+1)\ \mu(\omega)\ h_2 + (e^{2\kappa\Delta}-1)\ \mu_2\ \kappa$.

3. MAIN RESULTS

The results of numerical calculation of dispersion equations for E- and H-waves for the case $\varepsilon_1 = \varepsilon_2$, $\mu_1 = \mu_2$ and different left-handed slab thicknesses $\omega_0\Delta/c$ are shown at Fig. 1, 2. This case was analyzed in detail in our previous work [6]. The dispersion equations (4), (9) possesses six solutions. Curves marked by the numbers 1, 2, 3, 4 correspond to waves of E-type and curves marked by the numbers 5, 6 correspond to waves of H-type. For the chosen set of parameters the region when central material demonstrates left-handed properties (simultaneously $\varepsilon(\omega) < 0$ and $\mu(\omega) < 0$) lies in the region where $1 < \mu < 1.5$. A another regions with dispersions curves possesses plasma-like behavior $\varepsilon(\omega) < 0$ and $\mu(\omega) > 0$. The line (a) corresponds to $\xi = \sqrt{\varepsilon_{1,2}}\,\omega/c$, the line (c) corresponds to $\Omega = \omega/\omega_0 = 1$ and the line (b) - $\xi = \sqrt{\varepsilon(\omega)\mu(\omega)}\,\omega/c$.

The curved presented at Figs. 2, 3 corresponds to the waves of pure surface type [6, 7].

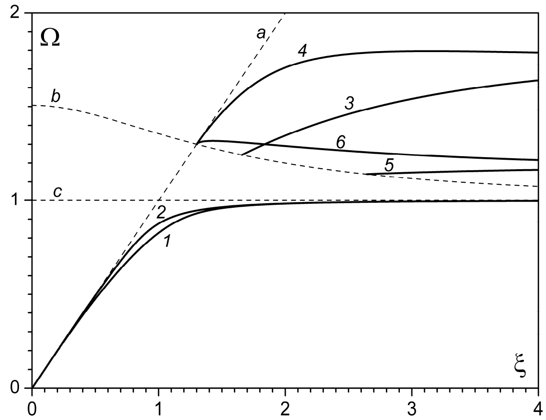

Fig. 1. The dependence of the normalized frequency $\Omega = \omega/\omega_0$ on dimensionless wave number $\xi = k_z c/\omega_0$ for left-handed material slab thickness $\omega_0\Delta/c = 0.6$, $\varepsilon_1 = \varepsilon_2 = 1$, $\mu_1 = \mu_2 = 1$

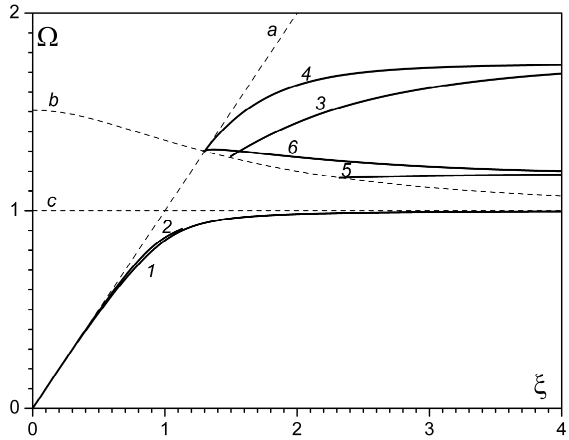

Fig. 2. The dependence of the normalized frequency $\Omega = \omega/\omega_0$ on dimensionless wave number $\xi = k_z c/\omega_0$ for left-handed material slab thickness $\omega_0\Delta/c = 0.9$, $\varepsilon_1 = \varepsilon_2 = 1$, $\mu_1 = \mu_2 = 1$

Properties of waves considered depend upon the left handed slab thickness $\omega_0\Delta/c$, especially for the waves that propagate in the slab that demonstrates plasma-like behaviour (see curves 1, 2 of Figs. 1, 2). The increase of left-handed material slab thickness leads to closing of the curves 1 and 2, 3 and 4, 5 and 6.

It was obtained that inequality in permittivity of conventional dielectrics ε_1 and ε_2 strongly effects on the electrodynamics characteristics of the waves considered. The results of the solution of the dispersion equations (4, 9) for $\varepsilon_1 = 1$, $\varepsilon_2 = 2$, $\mu_1 = \mu_2 = 1$ for rather thin ($\omega_0\Delta/c = 0.6$) and thick ($\omega_0\Delta/c = 0.9$) left handed material slab are presented at Figs. 3, 4.

The line (a) corresponds to $\xi = \sqrt{\varepsilon_1}\omega / c$, the line (d) corresponds to $\xi = \sqrt{\varepsilon_2}\omega / c$ other lines and curves have the similar meanings as for Figs. 1, 2.

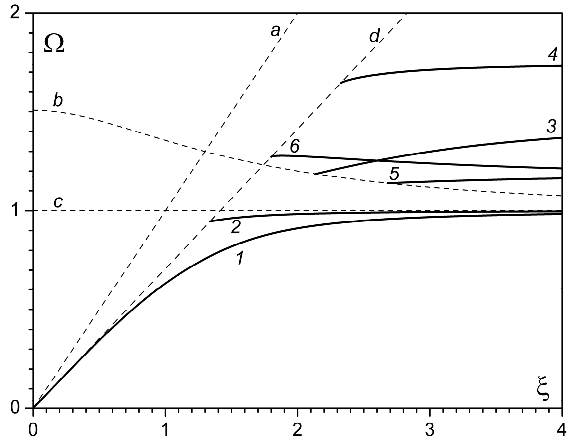

Fig. 3. The dependence of the normalized frequency $\Omega = \omega / \omega_0$ on dimensionless wave number $\xi = k_z c / \omega_0$ for left-handed material slab thickness $\omega_0 \Delta / c = 0.6$, $\varepsilon_1 = 1$, $\varepsilon_2 = 2$, $\mu_1 = \mu_2 = 1$

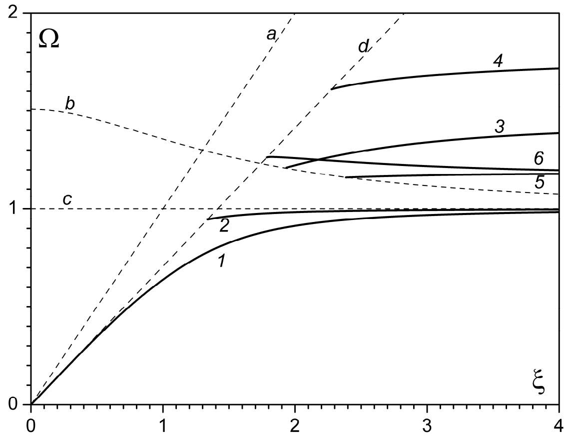

Fig. 4. The dependence of the normalized frequency $\Omega = \omega / \omega_0$ on dimensionless wave number $\xi = k_z c / \omega_0$ for left-handed material slab thickness $\omega_0 \Delta / c = 0.9$, $\varepsilon_1 = 1$, $\varepsilon_2 = 2$, $\mu_1 = \mu_2 = 1$

It was obtained that similarly with the case of $\varepsilon_1 = \varepsilon_2$ waves with both a forward and backward propagation can exist in this structure for the case $\varepsilon_1 \neq \varepsilon_2$.

It is necessary to mention that similarly to the case $\varepsilon_1 = \varepsilon_2$ Figs. 3, 4 possesses the region where E - and H - type waves with different group velocities can coexist for the same wave frequency and wave vector (curves 3, 6).

In the studied case $\varepsilon_1 \neq \varepsilon_2$ the regions were the waves can exists are reduced and the forbidden frequency regions become narrow. Also the absolute magnitude of group velocities became smaller. The curves 1 and 2 became separated. It is necessary to mention that the influence of left handed material slab thickness is much weaker that in the case when $\varepsilon_1 = \varepsilon_2$.

The results obtained can be useful for the future biophysical and image processing applications and others.

4. CONCLUSIONS

The dispersion properties and radial wave filed structure of electromagnetic waves in planar waveguide system with left-handed material slab bounded by semi-bounded dielectrics with different permittivity values were studied in this report.

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ЭЛЕКТРОМАГНИТНЫЕ ВОЛНЫ В СЛОЕ ЛЕВОСТОРОННЕГО МАТЕРИАЛА, ОГРАНИЧЕННОГО СРЕДАМИ С РАЗЛИЧНОЙ ДИЭЛЕКТРИЧЕСКОЙ ПРОНИЦАЕМОСТЬЮ

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Исследуются свойства поверхностных электромагнитных волн, распространяющихся вдоль плоской волноводной структуры, состоящей из слоя левостороннего материала, ограниченного обычными диэлектриками с различными значениями диэлектрической проницаемости. Показано, что различие в диэлектрических проницаемостях существенно влияет на дисперсию и радиальное распределение поля волны. Полученные результаты могут использоваться в дальнейшем для биофизических приложений, в обработке изображений и др.

ЕЛЕКТРОМАГНІТНІ ХВИЛІ У ШАРІ ЛІВОСТОРННЬОГО МАТЕРІАЛУ, ЩО ОБМЕЖЕНИЙ СЕРЕДОВИЩАМИ З РІЗНОЮ ДІЄЛЕКТРИЧНОЮ ПРОНИКЛИВІСТЮ

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Досліджено властивості поверхневих електромагнітних хвиль, що розповсюджується в пласкій хвилеводній структурі, що складається з шару лівостороннього середовища, що межує зі звичайними діелектриками з різними значеннями діелектричної проникливості. Показано, що різниця в діелектричних проникливостях суттєво впливає на дисперсію та радіальний розподіл поля хвилі. Отримані результати можуть бути використані у подальшому в біофізиці, обробці зображень та ін.