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SLOW ELECTROMAGNETIC WAVES IN PLANAR THREE-COMPONENT WAVEGUIDE STRUCTURE WITH MU-NEGATIVE METAMATERIAL

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This work is devoted to study of the dispersive properties of the slow electromagnetic waves that propagate along the planar waveguide structure that consists of semi-bounded plasma region, metamaterial slab and semi-bounded region of ordinary dielectric. It is studied the case when all media are homogeneous and isotropic. The dispersion properties, the phase and group velocities, as well as the electromagnetic field spatial structure of the eigen TE modes are studied in the frequency range where the metamaterial possess negative permeability.

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INTRODUCTION

During few decades there are both theoretical and experimental researches of artificially created man-made materials called metamaterials. These metamaterials have combinations of electrodynamics parameters that are do not occur in the nature [1 - 5].

Often this metamaterial are called "left-handed material" for the reason that in the unbounded medium, the three vectors of the electric, magnetic fields, and wave vector of a plane waves form the left triple. This is true for the metamaterials, in which the both permittivity and permeability are negative.

The properties of surface electromagnetic waves in the metamaterials were studied [6 - 13]. Were usually studied intensively the so-called double negative metamaterials, in which the negatives were both permittivity and permeability.

But it's no doubt, that creation of material with only negative permeability is easier that for the double negative ones [14]. In recent papers [15 - 17] were studied surface electromagnetic waves in such mu-negative metamaterials.

The fields of application are very wide ranging from the photovoltaic device development, the sensing and detection, the particles accelerators and many others [18 - 20].

In the present work, it has been studied slow electromagnetic waves that propagate in planar waveguide structures involving both mu-negative metamaterial and plasma.

1. TASK SETTING

The considered electromagnetic waves propagate in the planar three-component waveguide structure that consists of semi-bounded plasma-like region, mu-negative metamaterial slab of thickness d and semi-bounded region of ordinary dielectric.

The plasma medium is characterized by permittivity $\varepsilon_1(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$ here ω_p is an effective plasma frequency and permeability $\mu_1 = 1$. The metamaterial is characterized by permittivity $\varepsilon = \varepsilon_0$ and permeability that depend on the wave frequency and commonly expressed with the help of experimentally obtained expressions [2]:

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

Here ω_0 is the characteristic frequency of metamaterial, $\omega_0 / 2\pi = 4$ GHz and $F = 0.56$ [14].

Such parameters ratio leads to existence the frequency region where $\varepsilon_1(\omega) < 0$ and $\mu(\omega) < 0$ simultaneously. On other side near metamaterial slab is located the semi-bounded conventional dielectric with constant dielectric permittivity ε_2 and permittivity $\mu_2 = 1$.

Let's consider electromagnetic wave that propagates along this structure. It was assumed that wave disturbance tends to zero far away from metamaterial and the dependence of the wave components on time t and coordinate and z is expressed the following form:

$$E, H \propto E(x), H(x) \exp[i(k_3 z - \omega t)]. \qquad (2)$$

Here x is coordinate rectangular to the wave propagation direction and to the metamaterial slab.

It's possible in this case the system of Maxwell equations to split on two subsystems. One of them described the waves of *H*-type and another – the waves of *E*-type.

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

$$\begin{aligned}&\varepsilon_0(h_2\varepsilon_1 + h_1\varepsilon_2)\kappa \,\mathrm{Cosh}[d\kappa] + \\ &(h_1 h_2 \varepsilon_0^2 + \varepsilon_1\varepsilon_2\kappa^2)\,\mathrm{Sinh}[d\kappa] = 0.\end{aligned} \qquad (3)$$

Here $h_1 = \sqrt{k_3^2 - \varepsilon_1 k^2}$, $h_2 = \sqrt{k_3^2 - \varepsilon_2 k^2}$, $\kappa = \sqrt{k_3^2 - \varepsilon_0\,\mu(\omega) k^2}$, $k = \omega / c$, were c is the speed of light in vacuum.

In the plasma-like region ($x \le 0$) the wave field components, normalized on the $H_y(0)$, can be written as:

$$\begin{cases} H_y(x) = e^{h_1 x}, \\ E_x(x) = e^{h_1 x} k_3 / (\varepsilon_1 k), \\ E_z(x) = i\, e^{h_1 x} h_1 / (\varepsilon_1 k). \end{cases} \qquad (4)$$

In the region of metamaterial slab ($0 \le x \le d$) the wave field components, normalized on the $H_y(0)$, can be written as:

$$\begin{cases} H_y(x) = C_{1E} e^{\kappa x} + C_{2E} e^{-\kappa x}, \\ E_x(x) = k_3 \left(C_{1E} e^{\kappa x} + C_{2E} e^{-\kappa x} \right) / \left(k\, \varepsilon_0 \right), \\ E_z(x) = i\,\kappa \left(C_{1E} e^{\kappa x} - C_{2E} e^{-\kappa x} \right) / \left(k\, \varepsilon_0 \right). \end{cases} \quad (5)$$

Here C_{1E} and C_{2E} – are *E*-wave field constants.

In the dielectric region ($x \ge d$) the wave field components, normalized on the $H_y(0)$, possess the form:

$$\begin{cases} H_y(x) = B_E e^{-h_2 x}, \\ E_x(x) = B_E k_3 e^{-h_2 x} / \left(k\, \varepsilon_2 \right), \\ E_z(x) = -i\, B_E\, h_2 e^{-h_2 x} / \left(k\, \varepsilon_2 \right). \end{cases} \quad (6)$$

Here B_E is *E*-wave field constant. Such constants are of the following form:

$$\begin{cases} B_E = -2 h_1\, \varepsilon_2\, \varepsilon_0 e^{(h_2+\kappa) d} / \Psi_E, \\ C_{1E} = h_1\, \varepsilon_0 \left(h_2 \varepsilon_0 - \varepsilon_2\, \kappa \right) / \left(\kappa \Psi_E \right), \\ C_{2E} = -h_1\, \varepsilon_0 \left(h_2 \varepsilon_0 + \varepsilon_2 \kappa \right) e^{2\kappa d} / \left(\kappa \Psi_E \right). \end{cases} \quad (7)$$

Here $\Psi_E = \varepsilon_1 \left[(1 + e^{2\kappa d}) h_2\, \varepsilon_0 + (-1 + e^{2\kappa d}) \varepsilon_2\, \kappa \right]$.

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

$$\begin{aligned} &(h_1 + h_2)\kappa\, \mu(\omega) \mathrm{Cosh}[d\kappa] + \\ &(\kappa^2 + h_1\, h_2\, \mu^2(\omega)) \mathrm{Sinh}[d\kappa] = 0. \end{aligned} \quad (8)$$

In the plasma region ($x \le 0$) the wave field components, normalized on the $E_y(0)$, can be written as:

$$\begin{cases} E_y(x) = e^{h_1 x}, \\ H_x(x) = -e^{h_1 x} k_3 / k, \\ H_z(x) = -i\, e^{h_1 x} h_1 / k. \end{cases} \quad (9)$$

In the region of metamaterial slab ($0 \le x \le d$) the wave field components, normalized on the $E_y(0)$, can be written as:

$$\begin{cases} E_y(x) = C_{1H} e^{\kappa x} + C_{2H} e^{-\kappa x}, \\ H_x(x) = k_3 \left(C_{1H} e^{\kappa x} + C_{2H} e^{-\kappa x} \right) / \left(k\, \mu(\omega) \right), \\ H_z(x) = -i\,\kappa \left(C_{1H} e^{\kappa x} - C_{2H} e^{-\kappa x} \right) / \left(k\, \mu(\omega) \right). \end{cases} \quad (10)$$

Here C_{1H} and C_{2H} – are *H*-wave field constants.

In the dielectric region ($x \ge d$) the wave field components, normalized on the $E_y(0)$, possess the form:

$$\begin{cases} E_y(x) = B_H\, e^{-h_2 x}, \\ H_x(x) = k_3\, B_H\, e^{-h_2 x} / k, \\ H_z(x) = i\, B_H\, h_2 e^{-h_2 x} / k. \end{cases} \quad (11)$$

Here B_H is *H*-wave field constant. Such constants are of the following form:

$$\begin{cases} B_H = -2 h_1\, \mu(\omega)\, \varepsilon_0 e^{(h_2+\kappa) d} / \Psi_H, \\ C_{1H} = h_1\, \mu(\omega) \left[h_2\, \mu(\omega) - \kappa \right] / \left(\kappa \Psi_H \right), \\ C_{2H} = -h_1\, \mu(\omega) \left[h_2\, \mu(\omega) + \kappa \right] e^{2\kappa d} / \left(\kappa \Psi_H \right). \end{cases}$$

Here $\Psi_H = \kappa \left[(-1 + e^{2\kappa d}) \kappa + (1 + e^{2\kappa d}) h_2\, \mu(\omega) \right]$.

2. MAIN RESULTS

The results of numerical study of dispersion equations for *E*- and *H*-waves are shown at Fig. 1. The following dimensionless parameters were used to characterize the wave and the structure: normalized metamaterial slab thickness $\tilde{d} = \omega_0 d / c = 2.2$, normalized plasma frequency of the plasma-like media $\Omega_p = \omega_p / \omega_0 = 2.5$, $\varepsilon_2 = 1$, the normalized frequency $\Omega = \omega / \omega_0$ and the normalized wave number $\beta = k_3 c / \omega_0$.

In general case the dispersion equations (3), (8) have 3 solutions, including two waves of *H*-type and one wave *E*-type. Curves marked by the numbers 1, 2 correspond to waves of *H*-type (H_1-wave and H_2-wave) and curve marked by the numbers 3 correspond to wave of *E*-type (*E*-wave). The area to the right of the dashed line corresponds to the slow waves of surface type.

Thus, according to the example of a waveguide structure with parameters corresponding to Fig. 1, it can be concluded that the H_1-wave has the lowest frequency; the dispersion of this wave is straight in the entire range of wave numbers. The H_2-wave has a higher frequency Ω and in the region of small wavenumbers β the wave has a straight dispersion, but for the larger values the dispersion becomes reverse. In the region of the dispersion type changing the group velocity of the H_2-wave goes to zero. The *E*-wave of the structure possesses the highest frequency and wave numbers, the dispersion of this wave is straight in the entire range of wave numbers. The frequency ranges in which the eigenwaves of the structure exist do not intersect; these regions in Fig. 1 are shown by horizontal dashed lines.

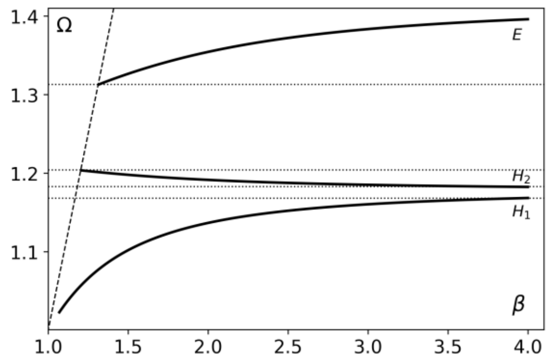


Fig. 1. The dependence of the normalized frequency $\Omega = \omega / \omega_0$ on the normalized wave number $\beta = k_3 c / \omega_0$ for normalized metamaterial slab thickness $\tilde{d} = \omega_0 d / c = 2.2$, normalized plasma frequency $\Omega_p = \omega_p / \omega_0 = 2.5$ and $\varepsilon_2 = 1$

In this work, a planar structure with normalized metamaterial thickness $\tilde{d} = \omega_0 \Delta / c = 2.2$ is investigated.

Under such parameters, in the region of not very short waves, it is possible to use the model of a dispersion medium with such magnetic permeability $\mu(\omega)<0$ that depends on the frequency according to the law (1).

The Fig. 2 shows the dependence of the dielectric permittivity of the plasma-like medium $\varepsilon_1(\omega)$ and the magnetic permeability of the metamaterial $\mu(\omega)$ upon the frequency for the structure with the parameters $\tilde{d}=\omega_0\Delta/c=2.2$, $\Omega_p=2$, $\varepsilon_2=1$. Vertical dashed lines show the bounds of the frequency intervals in which the eigenwaves of the considered planar waveguide structure can propagate. In the frequency range, where $\Omega<\Omega_p$, it was obtained that $\varepsilon_1(\Omega)<0$ for all eigenwaves of the structure. The next necessary condition $\mu(\Omega)<0$ is fulfilled for H_1- and H_2-eigenwave of the considered structure.

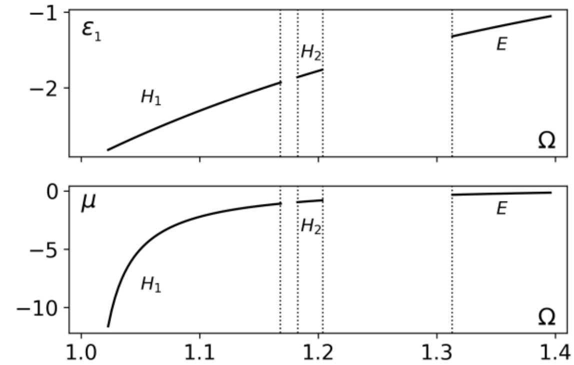


Fig. 2. The dependence of the dielectric permittivity of the plasma-like medium $\mu(\Omega)$ and the magnetic permeability of the metamaterial $\mu(\Omega)$ on the normalized frequency Ω for the structure parameters $\tilde{d}=\omega_0 d/c=2.2$, $\Omega_p=2$, $\varepsilon_2=1$

The paper presents the results of the study of the dispersion, phase and group speeds, spatial wave field structure of two eigenwaves of *H*-type, that propagate in the planar waveguide structure containing a metamaterial with a constant dielectric permittivity $\varepsilon=\varepsilon_0=1$ in the case when $\mu(\Omega)<0$.

Let us firstly presents the results of the study of H_1-wave properties. Let us determine the influence of the normalized plasma frequency $\Omega_p=\omega_p/\omega_0$ of the plasma-like medium and the dielectric permittivity ε_2 value of the medium that borders with metamaterial layer on the wave dispersion, phase and group speeds, and spatial wave field structure when $\varepsilon_1(\omega)<0$ and $\mu(\omega)<0$.

The dependence of the normalized frequency Ω for the H_1-wave upon the normalized wave number β for the waveguide structure with parameters $\Omega_p=2$ and $\varepsilon_2=1$ is shown in the Fig. 3.

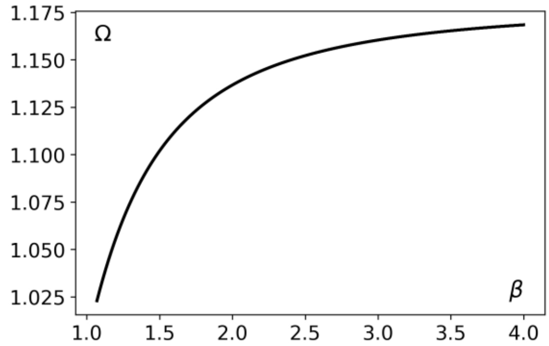


Fig. 3. The dependence of the normalized frequency $\Omega=\omega/\omega_0$ on normalized wave number β for the thickness of metamaterial slab $\tilde{d}=2.2$, $\Omega_p=2$, $\varepsilon_2=1$

The study have shown that the increase of the parameter Ω_p value from 2 to 10 practically does not influence on the wave dispersion, on the frequency range where the wave exists, and on the phase $V_{ph}(\Omega)$ and group $V_{gr}(\Omega)$ speeds that are shown in Fig. 4.

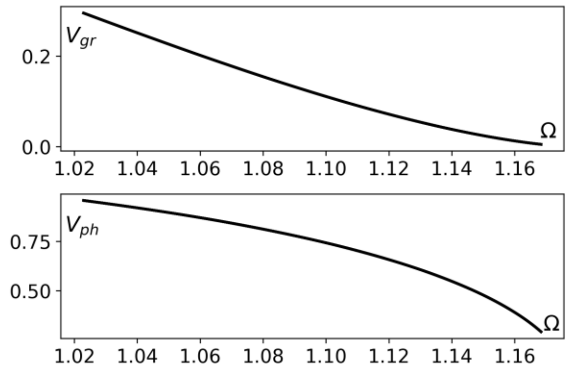
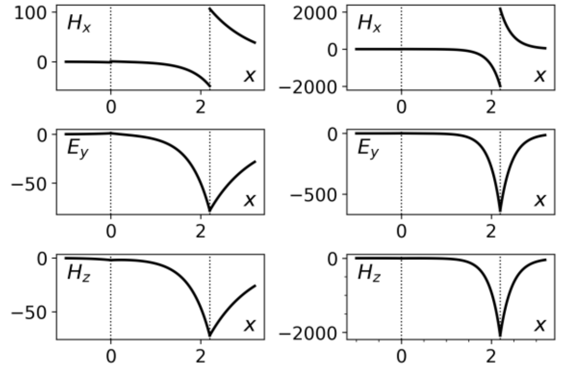


Fig. 4. The dependence of the normalized phase velocity $\tilde{V}_{ph}=V_{ph}/c$ and the normalized group velocity $\tilde{V}_{gr}=V_{gr}/c$ of the H_1-wave on the normalized frequency Ω for the structure parameters $\tilde{d}=2.2$, $\Omega_p=2$, $\varepsilon_2=1$

The maximum value of the group speed V_{gr} is reached in the region of low frequencies and the value does not exceeds the 0.3 of the speed of light in a vacuum and goes to zero as the frequency increases. The maximum value of the phase speed is reached in the region of low frequencies and is slightly less than the speed of light in a vacuum: $V_{ph}(\Omega)\approx 0.97$.

A similar dependence of the H_1-wave properties on the properties of the plasma-like medium becomes clear if one analyze the spatial distribution of the field of this wave for the structure with such set of parameters: $\Omega_p=2$ and $\varepsilon_2=1$. The results are shown in the Fig. 5,a for the point on the dispersion curve with the following values of the frequency $\Omega=1.102$ and the wave number $\beta=1.5$.



a) $\Omega = 1.102$, $\beta = 1.5$ *b)* $\Omega = 1.168$, $\beta = 4.0$

Fig. 5. The spatial distribution of the H_1-wave field components, normalized to $E_y(0)$ for the structure with the parameters corresponding to Fig. 3

For the studied waveguide structure, the H_1-wave is mainly concentrated at the metamaterial-dielectric interface and is practically absent in the plasma-like medium. When the wave frequency increases up to $\Omega = 1.168$, the wave number increases to $\beta = 4.0$. At the same time, the normalized values of the wave field components increase and the field penetration depth into the metamaterial and ordinary dielectric decreases, as shown in the Fig. 5,b.

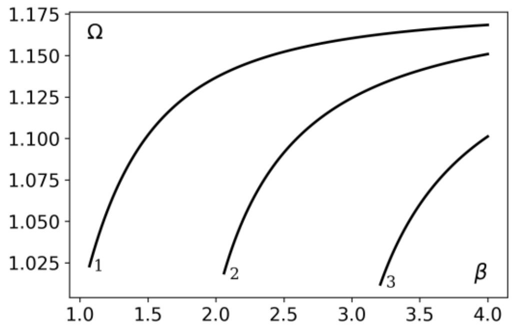


Fig. 6. The dependence of the normalized frequency Ω on normalized wave number β for thickness of metamaterial slab $\tilde{d} = 2.2$, $\Omega_p = 2$. The curve numbers 1, 2, 3 correspond the parameter $\varepsilon_2 = 1, 4, 10$ values

With such spatial distribution of the H_1-wave, its properties strongly depend on the dielectric permittivity ε_2 of the dielectric layer that borders with the metamaterial. In the Fig. 6 it is shown the dispersion of H_1-wave for the waveguide structure with parameters $\tilde{d} = 2.2$ and $\Omega_p = 2$ for three values of dielectric permittivity $\varepsilon_2 = 1.0; 4.0; 10$ (correspondent curves marked by the numbers 1, 2, 3).

The increase of the dielectric permittivity ε_2 value of the dielectric layer leads to the decrease of the normalized frequency of the wave Ω and to the decrease of the H_1-wave frequency range of existence.

More significant is the fact than under this ε_2 value growth the increase of the lower limit of normalized wave numbers take place. This leads to a significant decrease in the phase speed of the H_1-wave (Fig. 7), the maximum value of which at $\varepsilon_2 = 4$ decreases by almost at a half, as compared to wave phase speed when $\varepsilon_2 = 1$ (see Fig. 4).

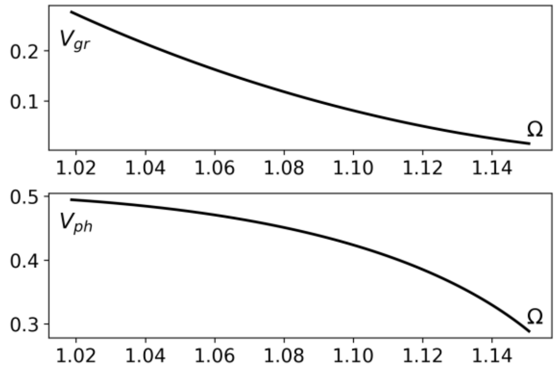
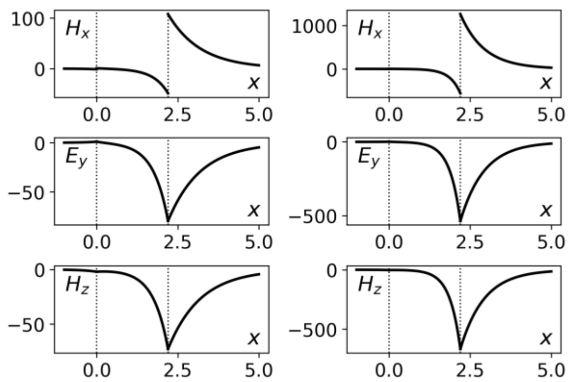


Fig. 7. The dependence of the normalized phase velocity $\tilde{V}_{ph} = V_{ph}/c$ and the normalized group velocity $\tilde{V}_{gr} = V_{gr}/c$ of the H_1-wave on the frequency Ω for the structure parameters $\Omega_p = 2$ and $\varepsilon_2 = 4$

When the dielectric permittivity value ε_2 increases from 1 up to $\varepsilon_2 = 4$ the maximum value of the normalized group speed $\tilde{V}_{gr}$ decreases from 0.28 to 0.23. The maximum value of the normalized phase speed $\tilde{V}_{ph}(\Omega)$ with such ε_2 value increase becomes almost twice smaller.

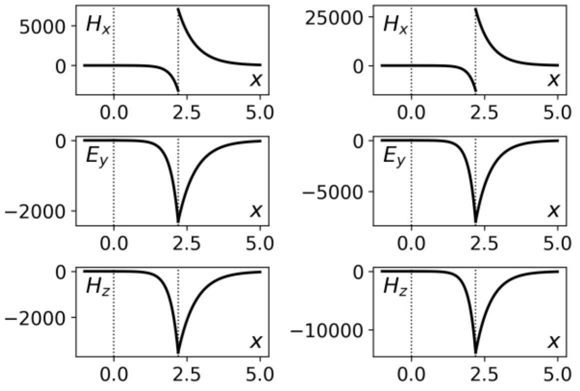
The influence of the dielectric permittivity ε_2 of the dielectric region on the spatial distribution of the H_1-wave field was also studied. In the Fig. 8,a,b it is shown the spatial distribution of the H_1-wave field components for the fixed wave frequency value $\Omega = 1.1$ in the waveguide structure with parameters $\Omega_p = 2$ and $\tilde{d} = 2.2$ for ordinary dielectrics with the following permeability values $\varepsilon_2 = 7.0; 10.0$; and in the Fig. 8,c,d – for dielectric with permeability values $\varepsilon_2 = 7.0; 10.0$.



a) $\varepsilon_2 = 1$; $\beta = 1.49$ *b)* $\varepsilon_2 = 4$; $\beta = 2.59$

Fig. 8.a,b. Spatial distribution of wave field components of the H_1-wave, normalized by the $E_y(0)$, for $\varepsilon_2 = 1.0; 4.0$

The value of the dielectric permittivity ε_2 has a weak influence on the wave field penetration depth into the metamaterial and the dielectric layers. At the same time, simultaneously with the ε_2 value growth, the value of the $H_x(x)$, $E_y(x)$, $H_z(x)$ wave field components at the metamaterial–dielectric interface, normalized by the electric field amplitude at the interface of the metamaterial with a plasma-like medium, increases significantly.



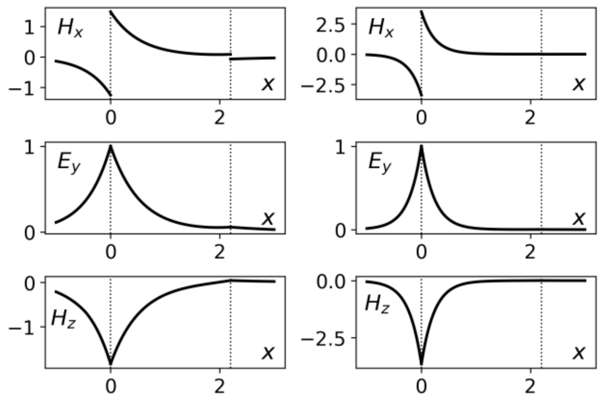
c) $\varepsilon_2 = 7$; $\beta = 3.36$ *d)* $\varepsilon_2 = 10$; $\beta = 3.97$

Fig. 8,c,d. Spatial distribution of wave field components of the H_1-wave, normalized by the $E_y(0)$, for $\varepsilon_2 = 7.0; 10.0$

Next, let us consider the properties of the H_2-wave that propagates along such a structure.

We will determine the influence of the normalized plasma frequency of the plasma-like medium $\Omega_p = \omega_p / \omega_0$ and the dielectric permittivity ε_2 of the medium, that borders with the metamaterial region, on the dispersion, phase and group speeds, and H_2-wave wave field spatial structure.

For a planar structure with a normalized width of the metamaterial layer $\tilde{d} = 2.2$, the amplitude values of the H_2-wave components reach their maximum value at the plasma-like medium – metamaterial layer interface $x = 0$.



a) $\Omega = 1.198$, $\beta = 1.5$, *b)* $\Omega = 1.183$, $\beta = 4.0$

Fig. 9. Spatial distribution of wave field components the H_2-wave, normalized by the $E_y(0)$, for the structure with parameters $\Omega_p = 2$ and $\varepsilon_2 = 1$

The Fig. 9 presents the spatial distribution of the H_2-wave field components in the studied structure with $\Omega_p = 2$ and $\varepsilon_2 = 1$ for different values of the normalized wave number β. The H_2-wave is localized at the interface between the metamaterial and the plasma-like medium. For the wave frequency value $\Omega = 1.102$ the wave number is equal to $\beta = 1.5$ (see Fig. 9,a). When the eigenwave frequency increases up to $\Omega = 1.1825$, the wavenumber increases to 4.0 (see Fig. 9,b). At the same time, the H_x and H_z components of the magnetic field of the H_2-wave, normalized by the $E_y(0)$, increased more than in 2.5 times. The field penetration depth into the both metamaterial and ordinary dielectric also decreases.

Such spatial wave field structure has as a consequence the fact that, unlike the H_1-wave, the properties of the H_2-wave depend on the normalized plasma frequency $\Omega_p = \omega_p / \omega_0$. The Fig. 10 presents the dispersion properties of the H_2-wave in the structure with a fixed value of $\varepsilon_2 = 1$ at different $\Omega_p = 2, 4, 10$ values (correspondent curves marked by the numbers 1, 2, 3). When the normalized plasma frequency increases, the normalized frequency of the H_2-wave and the value of the minimum possible wave number β value also increases.

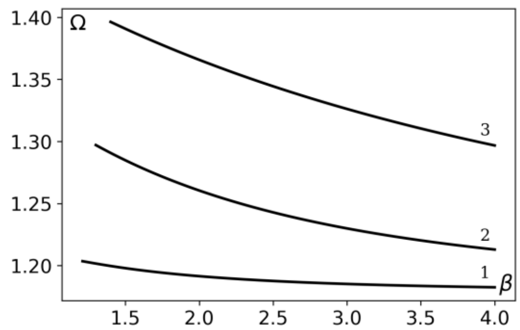


Fig. 10. The dependence of the normalized frequency Ω of the H_2-wave on normalized wave number β for the structure with parameters $\Omega_p = 2, 4, 10$ and $\varepsilon_2 = 1$

The Fig. 11 presents the influence of the normalized plasma frequency Ω_p on the phase and group speeds of the H_2-wave. The H_2-wave is the reversed because its phase and group velocities are opposite in sign.

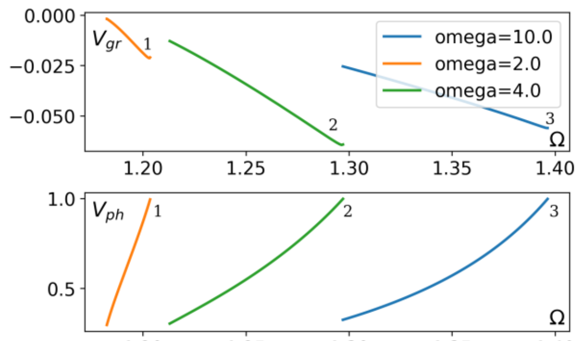


Fig. 11. The dependence of the normalized phase velocity $\tilde{V}_{ph}$ and the normalized group velocity $\tilde{V}_{gr}$ of the H_2-wave on the normalized frequency Ω for the structure with parameters that corresponds to Fig. 9

An increase in the normalized plasma frequency Ω_p leads to an increase in the absolute value of the H_2-wave group speed $\tilde{V}_{gr}$ and to the shift of the graph of $\tilde{V}_{gr}(\Omega)$ to the area of higher frequencies Ω.

The Fig. 12 presents the influence of the dielectric permittivity value of ε_2 the ordinary dielectric region that bounds the metamaterial slab at $x = d$, on the properties of H_2-wave that is localized at the interface of the plasma-like medium with metamaterial.

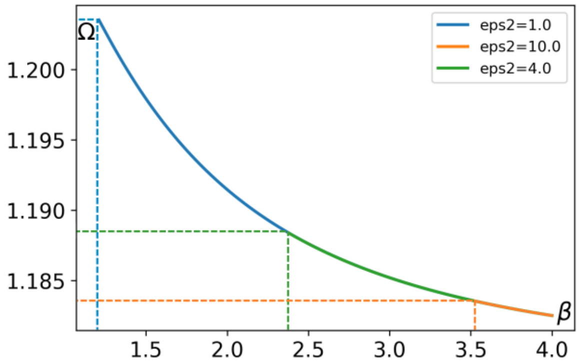


Fig. 12. The dependence of the normalized frequency Ω of the H_2-wave on normalized wave number β for the waveguide structure with $\Omega_p = 2$ for $\varepsilon_2 = 1, 4, 10$

The dispersion curve that corresponds to the $\varepsilon_2 = 1$ the starts at the leftmost point on the blue part of the curve and ends at the rightmost brown point at $\beta = 4.0$. The curve that corresponds to the $\varepsilon_2 = 4$ starts at the leftmost point on the green part of the curve and ends at $\beta = 4.0$. The curve that corresponds to $\varepsilon_2 = 10$ starts at the leftmost point on the part of the brown curve and ends at $\beta = 4.0$.

With the increase of the ε_2 value, the maximum value of the normalized frequency Ω decreases, and the corresponding values of the normalized wave number increase, which leads to a significant decrease in the frequency range where the H_2-wave can exist.

CONCLUSIONS

It is shown the possibility of the existence of two surface electromagnetic eigen waves with H-polarization that propagate along a planar waveguide structure consisting of a layer of homogeneous metamaterial whose permeability depends on frequency and is negative. The metamaterial is confined on the one side by a semi-bounded dispersion plasma-like medium, and on the other side by an semi-bounded ordinary dielectric.

It was obtained that the group and phase velocities of the H_1-wave, which has a lower frequency, coincide in the direction. It is shown that the phase and group velocities of the H_2-wave, which has a higher frequency, are directed opposite.

It was shown that the H_1-wave is localized near the interface of the metamaterial layer with a normal dielectric region, and for the normalized thickness of the metamaterial $\tilde{d} = 2.2$, its properties practically do not depend on the characteristics of the plasma-like medium.

The increase of the dielectric permittivity value ε_2 of the dielectric region leads to the decrease of the normalized wave frequency Ω and the H_1-wave frequency range. At the same time, the lower limit of the normalized wave numbers increases significantly and the H_1-wave phase speed decreases significantly.

It is shown that the H_2-wave is localized near the interface between the metamaterial layer and plasma-like medium region and its properties depend both on the characteristics of the plasma-like medium and on the permeability of the dielectric medium. The increase in the normalized plasma frequency Ω_p leads to the increase of the H_2-wave frequency interval of existence. At the same time, it is observed the increase of the absolute value of the wave group speed and a shift of the graph of $\tilde{V}_{gr}(\Omega)$ to the region of higher frequencies. The increase of Ω_p also leads to a shift of the phase velocity $\tilde{V}_{ph}(\Omega)$ graph to the region of higher frequencies.

It is shown that the increase of the dielectric permittivity ε_2 of the dielectric region leads to the decrease of the H_2-wave frequency range of existence and to the increase of the smallest possible value of the wave number.

The results obtained in the paper can be useful for modeling and creating of modern nano-devices based on the metamaterials.

REFERENCES

1. N. Engheta, R.W. Ziolkowski. *Metamaterials: Physics and Engineering Explorations*. New York: “Wiley”, 2006, 440 p.
2. L. Solymar, E. Shamonina. *Waves in Metamaterials* Oxford: “Oxford University Press”, 2009, p. xvi+385.
3. I. Mark. M. Stockman et al. Roadmap on plasmonics // *Journal of Optics*. 2018, v. 20, № 4, 043001.
4. *Theory and Phenomena of Metamaterials, edited by Filippo Capolino*. Boca Raton: “CRC Press”, 2009, 974 p.
5. S.A. Maier. *Plasmonics: Fundamentals and Applications.* Berlin: “Springer-Verlag”, 2007, 229 p.
6. R. Ruppin. Surface polaritons of a left-handed medium // *Phys. Lett. A*. 2000, v. 277, № 1, p. 61-64.
7. I. Shadrivov, A. Sukhorukov, Y. Kivshar. Guided modes in negative-refractive-index waveguides // *Phys. Rev. E.* 2003, v. 67, № 5, p. 057602.
8. G. D’Aguanno, N. Mattiucci, M. Scalora, M.J. Bloemer. TE and TM guided modes in an air waveguide with negative-index material cladding // *Physical Review E*. 2005, v. 71, № 4, p. 046603.
9. Ying He, Zhuangqi Cao, Qishun Shen. Guided optical modes in asymmetric left-handed waveguides // *Optics Communications*. 2005, v. 245, № 1-6, p. 125-135.

10. B. Wu, T. Grzegorczyk, Y. Zhang, and J. Kong. Guided modes with imaginary transverse wave number in a slab waveguide with negative permittivity and permeability // *J. Appl. Phys*. 2003, v. 93, № 11, p. 9386-9388.
11. K.L. Tsakmakidis et al. Surface plasmon polaritons in generalized slab heterostructures with negative permittivity and permeability // *Physical Review B.* 2006, v. 73, № 8, p. 085104.
12. Slobodan M. Vukovic, Najdan B. Aleksic, Dejan V. Timotijevic. Guided modes in left-handed waveguides // *Optics Communications*. 2008, v. 281, № 6, p. 1500-1509.
13. V.K. Galaydych, N.A. Azarenkov, V.P. Olefir, and A.E. Sporov. Surface electromagnetic waves on boundary between lossy dielectric and left-handed material with gain // *Problems of Atomic Science and Technology*. 2017, № 1, p. 96-99.
14. J.B. Pendry, A.J. Holden, D.J. Robbins, W.J. Stewart. Magnetism from conductors and enhanced nonlinear phenomena // *IEEE Trans. MTT*. 1999, v. 47, № 11, p. 2075-2084.
15. V. Galaydych, N. Azarenkov. Slow surface electromagnetic waves on a mu-negative medium // *Appied Physics B.* 2022, v. 128(7), p. 132.
16. V. Galaydych, A. Sporov. V. Olefir, N. Azarenkov. Slow surface eigenmodes directed by the mu-negative metamaterial slab // *East European Journal of Physics.* 2022, № 3, p. 77-83.
17. V. Galaydych, N. Azarenkov. Surface polaritons in a vacuum gap inside mu-negative medium // *Applied Physics A.* 2023, v. 129, p. 466.
18. S. Boriskina, G. Hadi, C. Gang. Plasmonic materials for energy: From physics to applications // *Materials Today.* 2013, v. 16, № 10, p. 375-386.
19. M. Stockman. Nanoplasmonic sensing and detection // *Science*. 2015, v. 348, № 6232, p. 287-288.
20. S. Antipov, W. Liu, W. Gai, J. Power, and L. Spentzouris. Double-negative metamaterial research for accelerator applications // *Nuclear Instruments and Methods in Physics Research.* 2007, A 579, № 3, p. 915-923.

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ПОВІЛЬНІ ЕЛЕКТРОМАГНІТНІ ХВИЛІ В ПЛАСКІЙ ТРИКОМПОНЕНТНІЙ ХВИЛЕВОДНІЙ СТРУКТУРІ З МЮ-НЕГАТИВНИМ МЕТАМАТЕРІАЛОМ

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Робота присвячена вивченню дисперсійних властивостей повільних електромагнітних хвиль, що розповсюджуються вздовж планарної хвилеводної структури, що складається з напівобмеженої області плазми, пластини метаматеріалу та напівобмеженої області звичайного діелектрика. Досліджується випадок, коли всі середовища однорідні та ізотропні. Досліджено дисперсійні властивості, фазову та групову швидкості, а також просторову структуру електромагнітного поля власних ТЕ-мод у діапазоні частот, де метаматеріал має негативну магнітну проникність.