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SLOW ELECTROMAGNETIC SURFACE TM-WAVES IN PLANAR WAVEGUIDE STRUCTURE WITH MU-NEGATIVE METAMATERIAL SLAB†

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In this work, we study the properties of slow electromagnetic surface TM-waves propagating along the planar waveguide structure involving the mu-negative metamaterial slab. The planar mu-negative metamaterial layer separates two semi-infinite regions: the plasma and the conventional dielectric. All media are assumed to be linear, homogeneous, and isotropic. The dispersion properties, the phase and group velocities, the spatial distribution of the electromagnetic fields of the TM mode in frequency range where the metamaterial has a negative permeability are under the consideration. The properties of this TM-eigenwave of the structure and two other TE modes are compared. It is studied the TM-eigenwave properties variation with metamaterial and plasma-like media properties changing. It is shown that for the considered structure, the properties of the TM mode depend significantly on the parameters of the plasma-like medium.
Keywords: *mu-negative metamaterial; plasma-like media; electromagnetic surface wave; wave dispersion properties; phase and group velocities; spatial wave structure*
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1. INTRODUCTION

In recent years, there has been an intensive study of the properties of metamaterials. These composite materials make it possible to create incredible combinations of electrodynamics parameters that are not found in nature [1-4]. Most often it was about the so-called "left-handed material" because in the unbounded medium, the vectors of the electric field, magnetic field, and wave vector of a plane waves form the left triple. This is valid for the double negative metamaterials, in which the both permittivity and permeability are negative. The properties of surface electromagnetic waves in the metamaterials were studied [5-13]. Mainly it was studied such double negative metamaterials.

It is an obvious fact that creation of material with only negative permeability is easier that for the double negative ones [14]. In a number of works [15-17] the properties of surface electromagnetic waves in such mu-negative metamaterials have been studied. The application areas of the considered modes are very wide from the signal transmission and processing, the sensing and detection, the particles accelerators, the photovoltaic 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.

2. TASK SETTING

Let's study the properties of the electromagnetic eigenwaves that propagate in the waveguide structure that consists of semi-infinite region of plasma-like media ($x \le 0$), the region of mu-negative metamaterial slab with thickness d ($0 \le x \le d$) and the semi-infinite region of conventional dielectric ($x \ge d$) (Fig. 1).

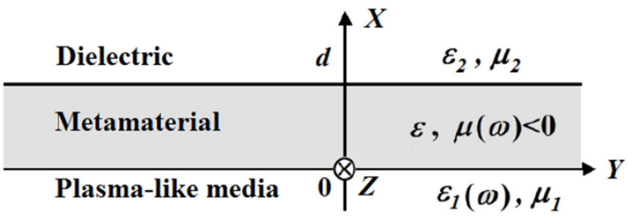

Figure 1. The studied waveguide structure

All media that construct the studied waveguide structure are considered to be homogeneous and isotropic. The plasma-like media is characterized by the wave frequency dependent permittivity $\varepsilon_1(\omega) = 1 - \omega_p^2/\omega^2$, where ω_p is effective plasma frequency, ω is the wave frequency and by the constant permeability $\mu_1 = 1$. The mu-negative

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metamaterial is characterized by the constant permittivity ε and the permeability that depends on the wave frequency and commonly expressed with the help of experimentally obtained expressions:

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

here ω_0 is the characteristic frequency of metamaterial, $\omega_0/2\pi=4$ GHz and $F=0,56$ [14]. It was studied further the frequency region where $\mu(\omega)<0$.

On other side of the mu-negative metamaterial slab the semi-infinite region of conventional dielectric with the constant permittivity ε_2 and permeability $\mu_2=1$ is located.

To study the propagation of the electromagnetic wave along the described structure it was assumed that the dependence of the wave components on time t and coordinate and z is expressed the following form:

$$E,H\propto E(x),H(x)\exp[i(k_3z-\omega t)], \tag{2}$$

here x is coordinate perpendicular to the wave propagation direction and to the metamaterial slab. It was also assumed that wave disturbance tends to zero far away from the metamaterial slab: $\lim\limits_{x\to\pm\infty} E(x),H(x)\to 0$.

For such case the system of Maxwell equations can be divided into two subsystems: one for the waves of H - type (*TE*-wave) and another – the waves of E - type (*TM*-wave). Taking into the account the boundary conditions (the continuity of the tangential electric and magnetic wave field components at the plasma-like medium - metamaterial interface and at the metamaterial – conventional dielectric interface) one can obtain the dispersion equation for the E - type wave in the following form:

$$\frac{h_1h_2\varepsilon_0^2+\kappa^2\varepsilon_1\varepsilon_2}{\kappa\varepsilon_0(h_2\varepsilon_1+h_1\varepsilon_2)}\tanh(d\kappa)+1=0, \tag{3}$$

here $h_1=\sqrt{k_3^2-\varepsilon_1k^2}$, $h_2=\sqrt{k_3^2-\varepsilon_2k^2}$, $\kappa=\sqrt{k_3^2-\varepsilon_0\,\mu(\omega)k^2}$, $k=\omega/c$, were c is the speed of light in vacuum.

The wave field components of the E -wave is naturally normalized on the $H_y(0)$ wave component. In the plasma-like region ($x\le 0$) these E -wave field components are expressed:

$$E_x^P(x)=\frac{e^{h_1x}k_3}{\varepsilon_1k},\ H_y^P(x)=e^{h_1x},\ E_z^P(x)=i\frac{e^{h_1x}h_1}{\varepsilon_1k} \tag{4}$$

The normalized E -wave field components in the region of metamaterial slab ($0\le x\le d$) can be written as:

$$E_x^M(x)=\frac{k_3}{k\varepsilon_0}\left(C_{1\mathrm{E}}e^{\kappa x}+C_{2\mathrm{E}}e^{-\kappa x}\right),\ H_y^M(x)=C_{1\mathrm{E}}e^{\kappa x}+C_{2\mathrm{E}}e^{-\kappa x},\ E_z^M(x)=\frac{i\kappa}{k\varepsilon_0}\left(C_{1\mathrm{E}}e^{\kappa x}-C_{2\mathrm{E}}e^{-\kappa x}\right) \tag{5}$$

here $C_{1\mathrm{E}}$ and $C_{2\mathrm{E}}$ – are E -wave field constants.

In the dielectric region ($x\ge d$) the normalized wave field components have the form:

$$E_x^D(x)=\frac{k_3}{k\varepsilon_2}B_{\mathrm{E}}e^{-h_2x},\ H_y^D(x)=B_{\mathrm{E}}e^{-h_2x},\ E_z^D(x)=-\frac{ih_2}{k\varepsilon_2}B_{\mathrm{E}}\,e^{-h_2x}, \tag{6}$$

here B_{E} is E - wave field constant. The constants $C_{1\mathrm{E}}$, $C_{2\mathrm{E}}$, B_{E} are also find from the boundary conditions and have the following form:

$$C_{1\mathrm{E}}=\frac{h_1\varepsilon_0\left(h_2\varepsilon_0-\varepsilon_2\kappa\right)}{\kappa\Psi_{\mathrm{E}}},\ C_{2\mathrm{E}}=-\frac{h_1\varepsilon_0\left(h_2\varepsilon_0+\varepsilon_2\kappa\right)}{\kappa\Psi_{\mathrm{E}}}e^{2\kappa d},\ B_{\mathrm{E}}=-\frac{2h_1\varepsilon_2\varepsilon_0}{\Psi_{\mathrm{E}}}e^{(h_2+\kappa)d} \tag{7}$$

here $\Psi_{\mathrm{E}}=\varepsilon_1\left((1+e^{2\kappa d})h_2\varepsilon_0+(-1+e^{2\kappa d})\varepsilon_2\kappa\right)$.

According to the similarly approach the dispersion equation for the wave of H - type can be obtained in the following form:

$$\frac{h_1h_2\mu^2(\omega)+\kappa^2}{(h_1+h_2)\kappa\mu(\omega)}\tanh(d\kappa)+1=0. \tag{8}$$

The wave field components of the H -wave is naturally normalized on the $E_y(0)$ wave component. In the plasma region ($x\le 0$) the H -wave field normalized components have the following form:

$$H_x^P(x) = -\frac{k_3}{k} e^{h_1 x},\ E_y^P(x) = e^{h_1 x},\ H_z^P(x) = -\frac{ih_1}{k} e^{h_1 x} \tag{9}$$

The normalized components of the H-wave in the region of metamaterial slab ($0 \le x \le d$) can be written as:

$$H_x^M(x) = \frac{k_3}{k\,\mu(\omega)}\left(C_{1\text{H}} e^{\kappa x} + C_{2\text{H}} e^{-\kappa x}\right),\ E_y^M(x) = C_{1\text{H}} e^{\kappa x} + C_{2\text{H}} e^{-\kappa x},\ H_x^M(x) = -\frac{i\kappa}{k\,\mu(\omega)}\left(C_{1\text{H}} e^{\kappa x} - C_{2\text{H}} e^{-\kappa x}\right) \tag{10}$$

here $C_{1\text{H}}$ and $C_{2\text{H}}$ – are H - wave field constants.

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

$$\begin{cases} E_y(x) = B_\text{H}\, e^{-h_2 x}, \\ H_x(x) = k_3\, B_\text{H}\, e^{-h_2 x} / k, \\ H_z(x) = i\, B_\text{H}\, h_2 e^{-h_2 x} / k, \end{cases} \tag{11}$$

here B_H is H - wave field constant. The constants $C_{1\text{H}}$, $C_{2\text{H}}$ and B_H can be also find from the boundary conditions and have the following form:

$$C_{1\text{H}} = \frac{h_1\,\mu(\omega)\left(h_2\,\mu(\omega) - \kappa\right)}{\kappa \Psi_\text{H}},\ C_{2\text{H}} = -\frac{h_1\,\mu(\omega)\left(h_2\,\mu(\omega) + \kappa\right)}{\kappa \Psi_\text{H}} e^{2\kappa d},\ B_\text{H} = -\frac{2\,h_1\,\mu(\omega)\,\varepsilon_0}{\Psi_\text{H}} e^{(h_2+\kappa)\,d} \tag{12}$$

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

3. MAIN RESULTS

To study the eigenwaves of the considered structure, let us use the following normalized variables and structure parameters: the normalized frequency $\Omega = \omega / \omega_0$ and the normalized wave number $\beta = k_3 c / \omega_0$, normalized metamaterial slab thickness $\tilde{d} = \omega_0 d / c$ and normalized plasma frequency of the plasma-like media $\Omega_p = \omega_p / \omega_0$. Further study is carried out for the waveguide structure with the fixed normalized metamaterial slab thickness $\tilde{d} = 2.2$ and the permittivity $\varepsilon = 1$. The dispersion properties of the E - and H - eigenwaves of the structure with conventional dielectric permittivity $\varepsilon_2 = 1$ and for two values of the plasma frequency $\Omega_p = 1.5$ and $\Omega_p = 2.0$ are shown in the Fig. 2, 3, respectively. The dashed lines on these both figures correspond to the condition $h_2(k_3, \omega) = 0$ and the region of the study corresponds to the region of the slow surface waves.

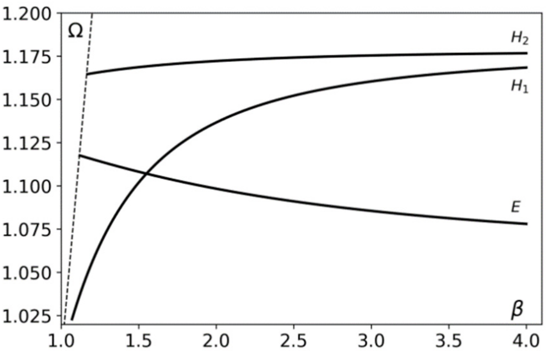


Figure 2. The dependence of the normalized frequency Ω on the normalized wave number β for normalized metamaterial slab thickness $\tilde{d}$, $\varepsilon_2 = 1$ and normalized plasma frequency $\Omega_p = 1.5$

In the studied waveguide structure only one E - wave and two H - waves can exist. In out further consideration the wave of H - type with lower frequency will be noted as H_1 - wave, and the wave of such polarization with larger frequency will be noted as H_2 - wave. The analysis of the dispersion properties of the eigenwaves of the considered structure shows that the variation of the normalized plasma frequency Ω_p has the greatest influence on the wave of E - type (see Fig. 2, 3). When Ω_p frequency value increases from 1.5 up to 2.0, the eigenfrequency of the E - wave also significantly increases with the changing of wave character – from backward wave for Ω_p = 1.5 to forward wave for Ω_p = 2.0.

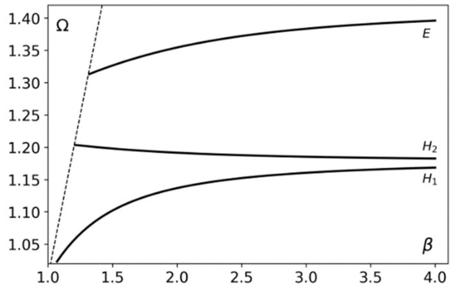
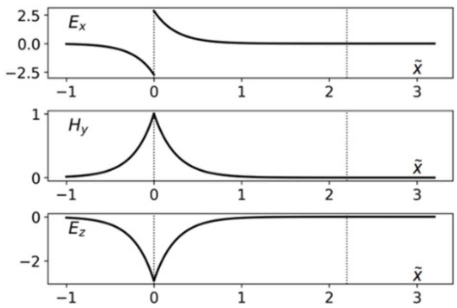


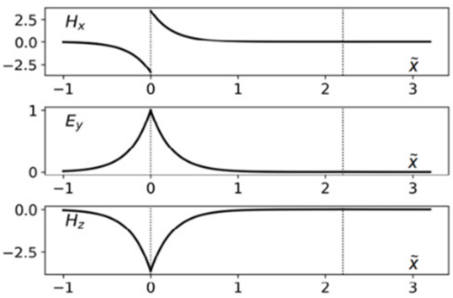
Figure 3. The dependence of the normalized frequency Ω on the normalized wave number β for normalized metamaterial slab thickness $\tilde{d} = 2.2$, $\varepsilon_2 = 1$ and normalized plasma frequency $\Omega_p = 2.0$

By changing the normalized plasma frequency Ω_p, it is also possible to influence the H_2 - wave characteristics, especially in the region of the smallest possible values of the normalized wave number β. With this mentioned increase of the Ω_p value, the H_2 - frequency in the region of small possible values of the normalized wave number increases more than with larger values $\beta = 4$. As a result of such Ω_p growth, not only the H_2 - wave frequency increases, but also changes the wave dispersion type, which becomes the reversed from the straight one. The indicated increase of the plasma frequency Ω_p practically does not change the dispersion of the H_1 - wave. Such influence of the plasma-like medium on the properties of the considered eigenwaves can be explained by analyzing the spatial distribution of the electromagnetic field components of the eigenwaves of the studied structure.

The Fig. 4a, 4b, 4c present the structure of wave field components for all three eigenwaves of the structure with parameters that are equal to parameters of the Fig. 3 and for the axial wave number k_3 =4.0. The normalized frequency Ω of the E - eigenwave is approximately equal to 1.39597 (Fig. 4a). The frequency of H_2 - eigenwave is approximately equal to 1.18341 (Fig. 4b) and approximately equal to 1.1676 for the H_1 - wave (Fig. 4c).



a



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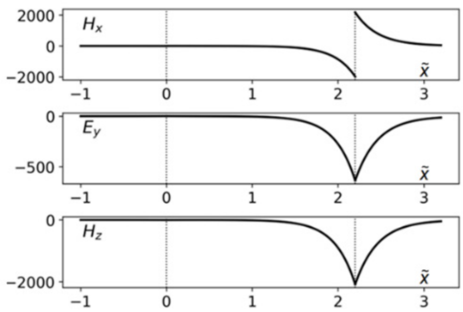

c

Figure 4. Spatial distribution of wave field components

a - the E - wave, normalized by the $H_y(0)$, $\tilde{x} = \omega_0 x / c$ - normalized x coordinate; b - the H_2 -wave, normalized by the $E_y(0)$; c - the H_1 -wave, normalized by the $E_y(0)$. The structure parameters corresponding to Fig. 3

Both the E - and H_2 - einegwaves of the structure are localized at the metamaterial - plasma-like medium interface. Thus, the significant influence of the plasma frequency value on these waves is quite understandable. As for the field of H_1 - wave, it is localized at the interface of the metamaterial - conventional dielectric interface $x = d$ and is practically equals to zero at the metamaterial's left boundary $x = 0$ (recall that the study is done for the normalized width of the metamaterial $\tilde{d} = 2.2$). This is the physical reason for the fact that properties of the plasma-like medium practically do not influence on the H_1 - wave properties. The spatial structure of the E - wave field that is presented in the Fig. 3a, explains the fact that its properties practically does not depend on the dielectric constant ε_2 of the conventional dielectric which restricts the metamaterial at $x = d$.

Let us note that the obtained strong influence of the plasma frequency on the E - wave properties requires a detailed analysis of the dependence of the frequency range of the E - wave existence, upon the parameters of the structure, are especially upon the normalized plasma frequency. This study can be done with the help of Fig. 5 which shows the dispersion of E - wave for different values Ω_p in the structure with $\tilde{d} = 2.2$, $\varepsilon_2 = 1$.

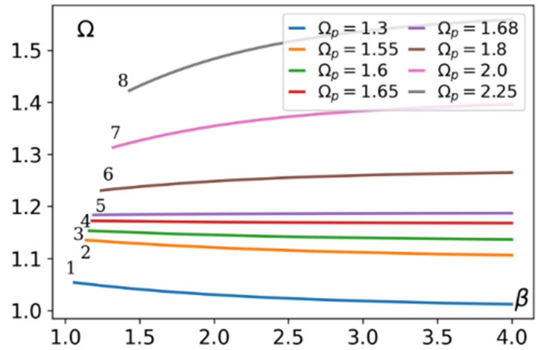

Figure 5. The dependence of the normalized frequency on the normalized wave number for normalized metamaterial slab thickness $\tilde{d} = 2.2$, $\varepsilon_2 = 1$ under different values of the normalized plasma frequency Ω_p

For the considered waveguide structure, the increase of the parameter Ω_p value in the range $1 < \Omega_p \le 2.255$ leads to the oncoming of the dispersion curve to some curve. Next, let us determine how the region of wave existence in frequency and wavenumber spaces changes its size due to an increase in the normalized plasma frequency of the plasma-like medium Ω_p . The carried-out study has shown that in the case when $\Omega_p = 1.3$ the interval of normalized eigenwave frequencies is $\{1.01195,\ 1.026\}$. The corresponding normalized wave numbers β relates to the interval $\{2.28,\ 4.0\}$.

With a further increase of Ω_p value up to 2.0, one can observe the shift of the wave frequency range to more high frequency region $\{1.36531,\ 1.39598\}$, but at the same time corresponding region of wave numbers does not change. With further plasma frequency Ω_p growth up to the 2.2 values, the shift of the wave frequency range towards the higher frequencies' interval $\{1.47631,\ 1.50728\}$. It is important that at the same time the range of allowed normalized wavenumber values of the E - wave significantly reduces to the interval $\{2.28,\ 3.04\}$. This means that with an unchanged lower limit of the possible β values, the upper limit of the range of β values becomes significantly smaller. When Ω_p value increases and becomes approximately equal to 2.255 the width of both wave frequency range $\{1.50624,\ 1.50749\}$ and wavenumber range $\{2.28,\ 2.3\}$.

Thus, with the increase of the normalized plasma frequency Ω_p the frequency of the E - eigenwave increases. At the same time, in the considered waveguide structures with $\varepsilon_2 = 1$ the frequency of the E - wave in the case when $\Omega_p < 1,6$ is less than the frequency of the H_1 - wave. In the case when $\Omega_p > 1,68$ the frequency of the E - wave is greater than the frequency of the H_2 - wave.

The carried out study have shown it is possible to find such normalized plasma frequency Ω_p value at which the frequency of the E - wave can coincide with the frequency of the H_1 - wave or with the frequency of the H_2 - wave that have the different polarization than the E - wave. At the same time it is necessary to note that frequencies of H_1 - and H_2 - waves with the same polarization belong to different frequency ranges.

So, it is necessary to mention that it is possible the situation when electromagnetic waves of different polarization can simultaneously propagate in the considered three-component waveguide structure composed of linear media. In particular, a situation is possible when the E - wave and H_2 - wave which localized at the boundary between the metamaterial and the plasma-like medium can simultaneously propagate in the structure (Fig. 6). Vertical dashed lines show the bounds of the frequency intervals in which the eigenwaves of the considered planar waveguide structure can propagate.

It should be noted that the overlap of the frequency ranges where H_1 and H_2 - type waves exist means that H_1 - and H_2 - wave with the same frequency but different wavelengths and significantly different spatial field structure can simultaneously propagate in the considered structure.

There is also possible the situation when a E - wave that propagates at the metamaterial - plasma-like medium interface can simultaneously propagate with H_1 - wave that propagates at the metamaterial - conventional dielectric interface.

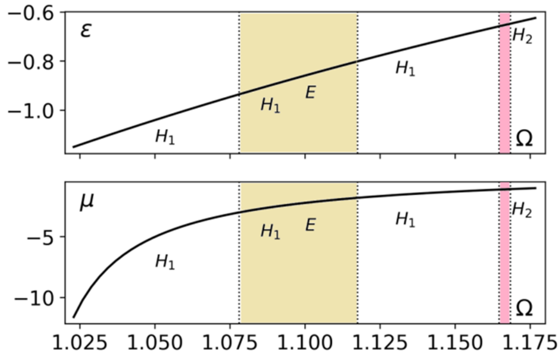

Figure 6. The dependence of the dielectric permittivity of the plasma-like medium $\varepsilon_1(\Omega)$ and the magnetic permeability $\mu(\Omega)$ of the metamaterial on normalized frequency Ω for the structure parameters $\tilde{d}=2.2$, $\varepsilon_2=1$, $\Omega_p=1.5$

So, let us note the important feature of this structure: due to changing the plasma frequency of plasma-like medium it is possible to provide a single-mode regime and it is possible to provide corresponding polarization of the eigenwaves that can propagate in the considered planar waveguide structure. From the point of view of the further possibility of application both similar waveguide structures and eigen-waves propagating in them, in addition to polarization, dispersion, spatial distribution of wave field components, it is important to analyze the influence of the normalized plasma frequency Ω_p on the phase and group velocity of the E - wave.

The Fig. 7 presents the dependence of the normalized phase velocity $\tilde{V}_{ph}=\omega/(k_3c)$ and the normalized group velocity $\tilde{V}_{gr}=(d\omega/dk_3)/c$ of the E - wave for different values of the normalized plasma frequency from the normalized wave frequency Ω. It is necessary to note the convenience of Fig. 7, the upper part of which shows the dependency $\tilde{V}_{gr}(\Omega)\big|_{\Omega_p}$ with the horizontal line $\tilde{V}_{gr}(\Omega)=0$, that separates the regions with different types of E - wave dispersion. It is presented how the increase of Ω_p value leads to the change of the dispersion type. For the chosen parameters set the value $\Omega_p=1.68$ is the value of group velocity sign changing. With the Ω_p value increase from 1 up to limiting value 1.68, the normalized group velocity, remaining negative, goes to zero. At the same time, the wave frequency range essentially decreases. When Ω_p value is greater than $\Omega_p>1.68$ the signs of the group and phase velocities coincide. The further increase of the plasma frequency Ω_p value up to 2.255 leads to the increase the E - wave group velocity.

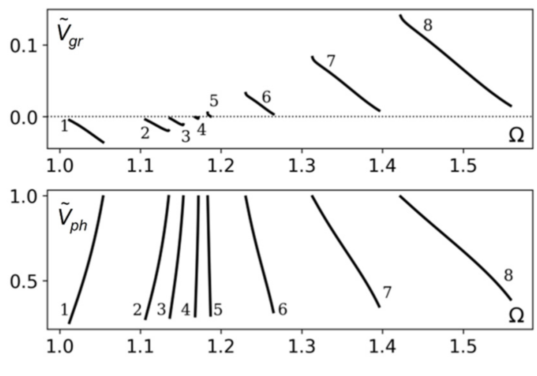

Figure 7. The dependence of the normalized phase velocity $\tilde{V}_{ph}=V_{ph}/c$ and the normalized group velocity $\tilde{V}_{gr}=V_{gr}/c$ of the E - wave on the normalized frequency for the structure parameters $\tilde{d}=2.2$, $\varepsilon_2=1$ under different values of the normalized plasma frequency Ω_p

At the same time the phase velocity of the E - wave for plasma frequency range $\Omega_p<1.68$ increases from the minimum value at the lower limit of the frequency range up to the speed of light in a vacuum at the upper limit of the frequency range. In the region when $\Omega_p>1.68$, the phase velocity of the E - wave decreases from a maximum value (close to the speed of light in a vacuum) at the lower limit of the frequency range to some minimum velocity value at the frequency range upper limit, which increases with the growth of Ω_p value.

The calculations have shown that for the considered waveguide structure the influence of the dielectric constant ε_2 of a conventional dielectric on the E - wave properties are practically absent.

CONCLUSIONS

The study has shown the possibility of one E - eigenwave and two H - eigenwaves propagation in a planar structure that is constructed with the metamaterial slab bounded on one side by a semi-infinite plasma-like medium, and on the other side by a conventional dielectric.

For the considered waveguide structure, it is determined the normalized plasma frequency Ω_p region in which the E - wave can propagates.

It is shown that the increase of Ω_p value leads to the significant increase of the E - eigenwave frequency. It is also defined range of Ω_p parameter values, where the wave dispersion changes its type.

It was found out that the E - eigenwave is localized at the metamaterial - plasma-like medium interface, where the H_2 - wave is also localized.

It is also shown the possibility of plasma frequency of the plasma-like medium Ω_p usage to ensure a single-mode regime and to select the polarization of the eigenwave in the considered planar waveguide structure.

It was also was determined the influence of Ω_p value as on the phase $\tilde{V}_{ph}(\Omega)$ and group $\tilde{V}_{ph}(\Omega)$ velocities of the E - eigenwaves, as on the regions of its wave numbers and frequencies, where the metamaterial possesses negative magnetic permeability.

The results obtained and presented in the article can be useful for modeling and creating modern devices based on metamaterials.

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ПОВІЛЬНІ ЕЛЕКТРОМАГНІТНІ ТМ-ХВИЛІ В ПЛАНАРНІЙ ХВИЛЕВОДНІЙ СТРУКТУРІ З ШАРОМ MU-НЕГАТИВНОГО МЕТАМАТЕРІАЛУ

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В роботі досліджуються властивості повільних електромагнітних поверхневих ТМ-хвиль, що поширюються вздовж планарної хвилеводної структури, до складу якої входить мю-негативна пластина метаматеріалу, що розділяє дві напівнескінченні області: плазму та звичайний діелектрик. Усі середовища вважаються лінійними, однорідними та ізотропними. Розглядаються дисперсійні властивості, фазова та групова швидкості, просторовий розподіл електромагнітного поля ТМ-хвилі в інтервалі частот, де метаматеріал має негативну магнітну проникність. Проведено порівняльний аналіз властивостей власних хвиль структури: однієї ТМ моди та двох ТЕ мод. Досліджено вплив параметрів структури на характеристики її власних хвиль. Показано істотну залежність властивостей ТМ моди структури, що розглядається, від параметрів плазмоподібного середовища. Отримано, що збільшення значення плазмової частоти плазмоподібного середовища призводить до значного збільшення частоти власної ТМ-хвилі. Було визначено діапазон значень плазмової частоти, за яких ця хвиля змінює тип дисперсії. Визначено, що власна E -хвиля локалізована на межі розподілу між мета матеріалом та плазмоподібним середовищем, де також локалізована H_2 - хвиля - одна з хвиль з *TE* поляризацією та частотою дещо більшою за частоту H_1 - хвилі. Було показано можливість забезпечення одномодового режиму та вибору потрібної поляризації власної хвилі в розглянутій планарній хвилеводній структурі за рахунок вибору значення плазмової частоти плазмоподібного середовища. Було вивчено також вплив цієї частоти на значення як фазових, так і групових швидкостей власних E -хвиль. Отримані результати можуть бути корисними для моделювання та створення сучасних пристроїв на основі метаматеріалів.

Ключові слова: *мю-негативний метаматеріал; плазмоподібні середовища; електромагнітна поверхнева хвиля; хвильові дисперсійні властивості; фазові та групові швидкості; просторова хвильова структура*