East European Journal of Physics. 3. 77-83 (2022)
DOI:10.26565/2312-4334-2022-3-10 ISSN 2312-4334

SLOW SURFACE EIGENMODES DIRECTED BY THE Mu-NEGATIVE METAMATERIAL SLAB[†]

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Received July 10, 2022; revised August 8, 2022; accepted August 15, 2022

The paper presents the results of the study of slow surface electromagnetic waves directed along the flat mu-negative metamaterial slab surrounded by ordinary dielectric material. It is considered the case of isotropic and homogeneous metamaterial without losses. This metamaterial possesses the positive permittivity and the negative permeability over a definite frequency band. It is found that two surface modes of TE polarization can propagate along such waveguide structure. The dispersion properties, the spatial distribution of the electromagnetic field, as well as the phase and group velocities of these slow modes are studied. The first mode is a conventional forward wave, and has a lower frequency and lower phase velocity than the second mode. The second mode may have zero group velocity at a certain frequency. Characteristics of these surface modes for different values of the mu-negative slab parameters have been studied. The studied surface electromagnetic waves can be used for practical applications as in laboratory experiments, as in various technologies.

Keywords: mu-negative metamaterial; electromagnetic surface wave; wave dispersion properties; spatial wave structure
PACS: 52.35g, 52.50.Dg

In recent years it was carried out the intensive study of the artificially created materials with special extraordinary electromagnetic properties – so called metamaterials. Such metamaterials are the innovative composite materials that consist of artificially constructed periodical structure of small-size units that play the role of atoms for electromagnetic waves. The main aim of creation of such innovation is to get definite combinations of electromagnetic characteristics that do not occur in nature. Firstly, the main attention of researches was paid to the double negative (so-called left-handed) metamaterials, with simultaneously negative value of permittivity and permeability [1,2]. These left-handed metamaterials are mainly interested with the possibility of realizing a negative refractive index for the creation of ideal lenses and other devices which contain such metamaterials [3-9]. Next, for these purposes there were also created mono-negative metamaterials, for example, with positive permittivity and negative permeability values – so called mu-negative metamaterials [10,11]. No doubt that creating such mono-negative metamaterials is easier in comparison with double-negative ones [2]. Just now it was found that along the interface between a medium with negative permeability and vacuum the surface electromagnetic waves can propagate [11]. The real devices are spatially bounded, so it is necessary to study the electrodynamic properties of the waveguide structure with flat mu-negative metamaterial slab surrounded by ordinary dielectric material. In this paper we represent a new surface electromagnetic eigenmodes that can propagate along such waveguide structure.

TASK SETTINGS

Let us study the electrodynamic properties of waveguide structure that is composed of mu-negative metamaterial layer with thickness d with negative permeability $\mu(\omega)<0$ and constant positive permittivity ε. The coordinate axis X is directed along this slab (Fig. 1).

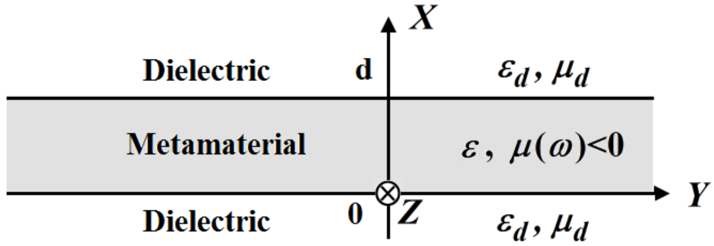

Figure 1. The geometry of problem

This metamaterial slab in immersed into ordinary unbounded dielectric without losses with permittivity ε_d and permeability μ_d. Further study was carried out for the waveguide structure with permittivity $\varepsilon = 1$, and permeability

[†] ***Cite as:*** V.K. Galaydych, O.E. Sporov, V.P. Olefir, and M.O. Azarenkov, East Eur. J. Phys. **3**, 77 (2022), https://doi.org/10.26565/2312-4334-2022-3-10

$\mu(\omega)$ that depends on the circular wave frequency ω according to the following law, which is in accordance with the experimental data [10]

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

where ω_0 – is the characteristic frequency of the metamaterial and in our case $\omega_0 / 2\pi = 4$ ГГц; the parameter $F = 0.56$.

Let study slow electromagnetic waves, that propagate along flat waveguide structure in the direction of the Z axis (Fig. 1). It was assumed that the wave disturbances exponentially tend to zero far away from both boundaries. The dependence of the wave components on time t and coordinates x and z are expressed the following form:

$$E, H \propto E(x), H(x)\exp[i(k_3 z - \omega t)], \tag{2}$$

here z lies at the separation plane, and x is the coordinate rectangular to the wave propagation direction and k_3 – is the longitudinal wavenumber.

In the considered case it is possible to split the system of Maxwell equations in to two sub-systems. One of them describes TE-waves and another – TM- waves.

Let us find the solution of the Maxwell system of equations for TE-wave that satisfy the boundary conditions at the interface between the metamaterial and the dielectric. As a result, one can obtain the wave field components and the dispersion equation of the eigen electromagnetic E-wave (TM-wave) of the considered planar structure.

The wave field components of the E-wave in the dielectric region $x \le 0$ can be written as:

$$\begin{cases} H_y(x) = H_y(0)e^{h_d x}, \\ E_x(x) = H_y(0)k_3 e^{h_d x} c / (\varepsilon_d\, \omega), \\ E_z(x) = i\, H_y(0)h_d e^{h_d x} c / (\varepsilon_d\, \omega), \end{cases} \tag{3}$$

where c – is speed of light in vacuum.

The wave field components of the E-wave in the metamaterial region $0 \le x \le d$ can be found in the following form:

$$\begin{cases} H_y(x) = H_y(0)\left[cosh(\kappa x) + \dfrac{h_d \varepsilon\, sinh(\kappa x)}{\varepsilon_d \kappa}\right], \\ E_x(x) = H_y(0)\dfrac{ck_3}{\varepsilon\varepsilon_d \kappa\omega}\left[\varepsilon_d \kappa\, cosh(\kappa x) + h_d \varepsilon\, sinh(\kappa x)\right], \\ E_z(x) = H_y(0)\dfrac{ic}{\varepsilon\varepsilon_d \omega}\left[h_d \varepsilon\, cosh(\kappa x) + \varepsilon_d \kappa\, sinh(\kappa x)\right]. \end{cases} \tag{4}$$

The wave field components of the E-wave (TM-wave) in the dielectric region $x \ge d$ may be expressed as:

$$\begin{cases} H_y(x) = H_y(0)e^{h_d(-x+d)}\left[\dfrac{\varepsilon_d \kappa\, cosh(\kappa d) + h_d \varepsilon\, sinh(\kappa d)}{\varepsilon_d \kappa}\right], \\ E_x(x) = H_y(0)\dfrac{ck_3}{\varepsilon_d^2 \kappa\omega} e^{h_d(-x+d)}\left[\varepsilon_d \kappa\, cosh(\kappa d) + h_d \varepsilon\, sinh(\kappa d)\right], \\ E_z(x) = -H_y(0)\dfrac{ich_d}{\varepsilon_d^2 \kappa\omega} e^{h_d(-x+d)}\left[\varepsilon_d \kappa\, cosh(\kappa d) + h_d \varepsilon\, sinh(\kappa d)\right]. \end{cases} \tag{5}$$

The dispersion equation for the E-wave (TM-wave) has the following form:

$$2h_d \varepsilon\varepsilon_d \kappa\, cosh(\kappa d) + \left(h_d^2 \varepsilon^2 + \varepsilon_d^2 \kappa^2\right) sinh(\kappa d) = 0, \tag{6}$$

where $h_d = h_d(k_3, \omega) = \sqrt{k_3^2 - \varepsilon_d \cdot \mu_d \cdot k^2}$ – is transversal wave number in dielectric region, $k = \omega / c$ – the wavenumber in vacuum; $\kappa = \kappa(k_3, \omega) = \sqrt{k_3^2 - \varepsilon \cdot \mu(\omega) \cdot k^2}$ – the transversal wavenumber in metamaterial.

Analogous computations for TM- wave leads to the equations for the wave field components and the dispersion equation of the eigen electromagnetic H-wave (TE-wave) of the considered flat waveguide structure.

The wave field components of the electromagnetic H-wave (TE-wave) in dielectric region $x \le 0$ may be written as:

$$\begin{cases} E_y(x) = E_y(0)e^{h_d x}, \\ H_x(x) = -E_y(0)ck_3 e^{h_d x} / (\mu_d\, \omega), \\ H_z(x) = -i\, E_y(0)ch_d e^{h_d x} / (\mu_d\, \omega). \end{cases} \tag{7}$$

The wave field components of the electromagnetic H-wave (TE-wave) in metamaterial region $0 \le x \le d$ has the following form:

$$\begin{cases} E_y(x) = E_y(0)e^{h_d x}\left[cosh(\kappa x) + \dfrac{h_d \mu\, sinh(\kappa x)}{\mu_d \kappa}\right], \\ H_x(x) = -E_y(0)\dfrac{ck_3}{\kappa\mu\mu_d\omega}\left[\kappa\mu_d\; cosh(\kappa x) + h_d \mu\; sinh(\kappa x)\right], \\ H_z(x) = -\,E_y(0)\dfrac{ic}{\mu\mu_d\omega}\left[\mu h_d\; cosh(\kappa x) + \kappa\mu_d\; sinh(\kappa x)\right]. \end{cases} \tag{8}$$

The wave field components of the electromagnetic H-wave (TE-wave) in dielectric region $x \ge d$ can be written as:

$$\begin{cases} E_y(x) = E_y(0)e^{h_d(-x+d)}\left[\dfrac{\kappa\,\mu_d\; cosh(\kappa d) + h_d \mu\; sinh(\kappa d)}{\mu_d \kappa}\right], \\ H_x(x) = -E_y(0)\dfrac{ck_3}{\kappa\,\mu_d^2\,\omega}e^{h_d(-x+d)}\left[\kappa\,\mu_d\; cosh(\kappa d) + h_d\,\mu\;\; sinh(\kappa d)\right], \\ H_z(x) = E_y(0)\dfrac{ich_d}{\kappa\,\mu_d^2\,\omega}e^{h_d(-x+d)}\left[\kappa\,\mu_d\; cosh(\kappa d) + h_d\,\mu\;\; sinh(\kappa d)\right]. \end{cases} \tag{9}$$

The dispersion equation for the electromagnetic H-wave (TE-wave) can be written in the following form

$$2h_d \kappa\mu\mu_d\; cosh(\kappa d) + \left(h_d^2 \mu^2 + \kappa^2 \mu_d^2\right) sinh(\kappa d) = 0\,. \tag{10}$$

RESULTS AND DISCUSSION

Let study the properties of the waves that govern by the dispersion equations (6, 10) for the arbitrary set of parameters. It was shown that in the frequency range when the metamaterial is mu-negative the equation for the TM-wave (6) has no solutions and only the equation (10) for TE-wave has the solutions. To study the properties of these solutions let us introduce the following dimensionless quantities: the normalized circular frequency $\Omega = \omega / \omega_0$, normalized wavenumber $\beta = k_3 c / \omega_0$ and normalized thickness of the metamaterial layer $\Delta = d\ \omega_0 / c$.

The solutions of the dispersion equation (10) for the TE modes for the such set of parameters: $\varepsilon = 1$, $\varepsilon_d = 1$, $\mu_d = 1$, $\Delta = 0.4$ (the case of thin metamaterial slab) are presented at Fig. 2, 3. It was found that the dispersion equation (10) possesses two eigen solutions that are shown at Fig. 2.

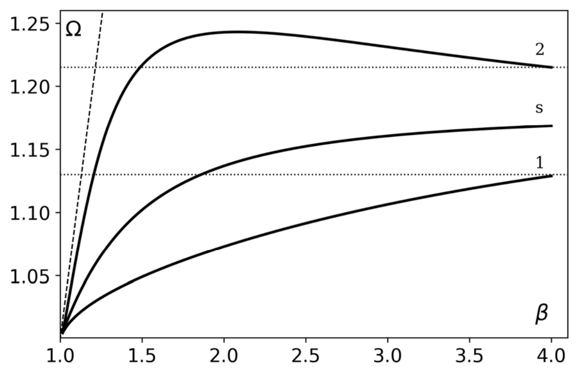

Figure 2. The solution of the dispersion equation (10) for TE-modes for $\varepsilon = 1, \varepsilon_d = 1, \mu_d = 1$, $\Delta = 0.4$. The curves marked by the numbers 1 and 2 corresponds to the two eigenmodes of waveguide structure. Line marked by the letter ‘s’ corresponds to the eigen wave of the simplified model, presented in [12].

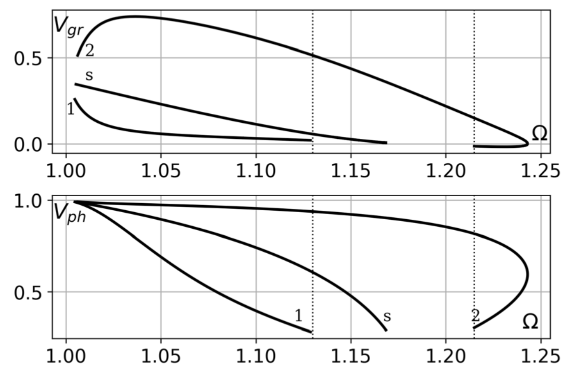

Figure 3. The group V_{gr} and phase V_{ph} normalized velocities of TE modes presented on the Figure 2. The parameters set and curve numbering are the same as for the Figure 2.

The presented solutions (eigenmodes of TE-type) of the dispersion equation (10) for the studied model are marked by the numbers 1 and 2. The line, marked by the letter ‘s’ corresponds to the single eigenwave of the simplified waveguide model, presented in [12] under the same parameter set. The further analysis has shown that this solution for the simplified model corresponds to the low frequency solution (curve 1) for the model considered.

The mutual location of the dispersion curves 1 and 2 in Fig. 2 indicates the existence of three different regions of the frequency interval. In the Fig. 2 these regions are separated from each other by the dashed horizontal lines. In the first frequency region $1.04 < \Omega < 1.13$ two modes of TE-type that corresponds to different solutions of the dispersion equation (10) with the same frequency can simultaneously propagate in the considered flat bounded structure. In the second frequency region $1.13 < \Omega < 1.215$ the excitation of only one mode that corresponds to the solution 2 with harmonic spatial dependence is possible. Finally, in the third frequency region $1.215 < \Omega < 1.243$, the propagation of two harmonic waves that corresponds to the solution 2 with the same frequency, but with different wavelengths takes place.

Figure 3 presents the dependence of the group V_{gr}=c$^{-1}d\,\omega / d\,k_3$ and phase V_{ph}=ω/(k$_3$$c$) normalized velocities for two eigen TE-modes upon the normalized frequency Ω. The parameters set and curve numbering are the same as for the Figure 2. One can see the analogous to Figure 2 three frequency regions that are separated from each other by the dashed vertical lines in Fig. 3. In the first frequency region $1.04 < \Omega < 1.13$ one can observe two slow modes that simultaneously propagate in the considered flat structure with the same frequency. These two modes possess group and phase velocities that coincide in direction but have different values, respectively. In the second frequency range $1.13 < \Omega < 1.215$ it is possible the excitation of slow mode 2 only. The phase velocity of this wave is about 0.9 of the speed of light, and its group velocity decreases with the frequency increase from $0.5c$ down to $0.2c$ according to an almost linear law. In the third frequency region $1.215 < \Omega < 1.243$ one can observe the propagation of two harmonic waves of the mode 2 with the same frequency but different wavelengths. The group velocities of these waves are of different signs.

The spatial wave field structure of such waves is presented in Figs. 4, 5. The calculations are carried out for the same parameters set as for the Figs. 2, 3: $\varepsilon = 1$, $\varepsilon_d = 1$, $\mu_d = 1$, $\Delta = 0.4$. The wave field components, normalized by the $E_y(0)$ are calculated for $\beta = 4$ and obtained from the dispersion equation (10) eigen frequency value $\Omega = 1.1288$ for the mode 1 (see Fig. 4), and for the $\Omega = 1.21496$ for the mode 2 (see Fig. 5).

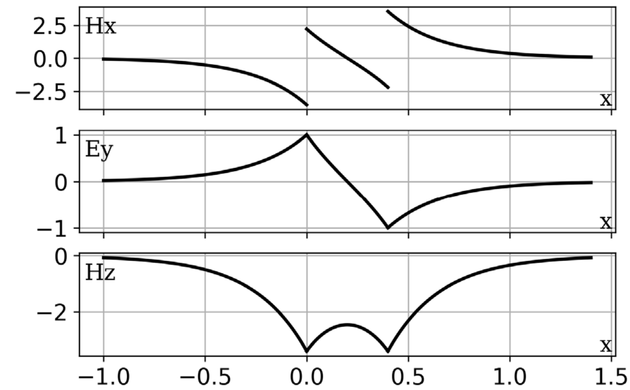

Figure 4. The wave field components normalized on the $E_y(0)$ for the mode 1 in the Fig. 2. The parameters set are the same as was used for the Fig. 2. The wave field structure is calculated for $\beta = 4$ and eigen wave frequency $\Omega = 1.1288$.

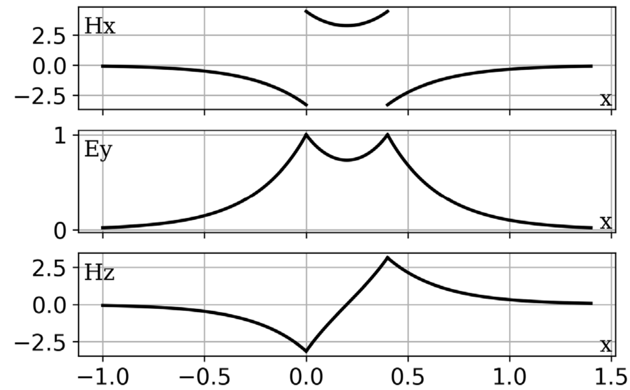

Figure 5. The wave field components normalized on the $E_y(0)$ for the mode 2 in the Fig. 2. The parameters set are the same as was used for the Fig. 2. The wave field structure is calculated for $\beta = 4$ and eigen wave frequency $\Omega = 1.21496$.

The solutions of the dispersion equation (10) in the case of rather thick metamaterial slab for the TE modes for the such set of parameters: $\varepsilon = 1$, $\varepsilon_d = 1$, $\mu_d = 1$, $\Delta = 0.8$ are presented at Fig. 6, 7. The numbering of the curve are the same as for the Fig. 2.

The increase of the metamaterial layer thickness leads to the gradually convergence of the both curves 1 and 2 to each other, and to the solution of the simplified waveguide model, presented in [12] under the same parameter set (see Fig. 8). This figure presents the variation of the wave eigen frequency Ω obtained due to the solution of the dispersion equation (10) when $\varepsilon = 1$, $\varepsilon_d = 1$, $\mu_d = 1$ for $\beta = 4$ while normalized metamaterial slab thickness varies from $\Delta = 0.4$ up to $\Delta = 0.8$.

Also, the increase of metamaterial thickness Δ leads to the frequency ranges change. So, for the increase of Δ from 0.4 up to 0.8 results in the increase of the first frequency range and the decrease of the second, and especially third frequency ranges where the only wave 2 can exist (see Fig. 6). The region where the TE mode 2 has negative group frequency value became extremely small (see Fig. 7). So, one can effectively control the propagation properties of TE modes due to the variation of metamaterial slab thickness.

The wave spatial wave structure for the mode 2 for the parameters set analogous to that of Fig. 6 for the region, where wave group velocity tends to zero: $V_{gr} \sim 0$ ($\beta \approx 2.804$, $\Omega \approx 1.178$) is presented at Fig. 8. This wave is of a surface wavy type and can be treated as the standing wave due to superposition of two TE type 2 modes that have equal both frequencies and wavenumber but propagate in opposite directions.

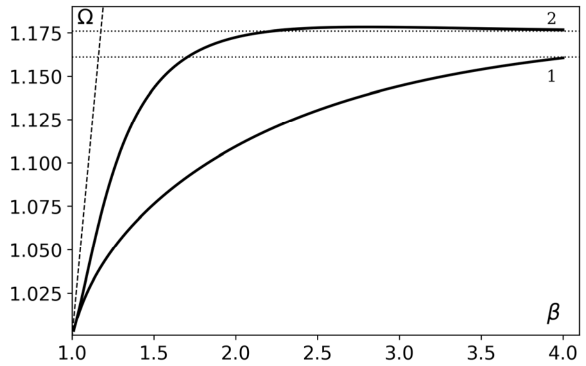

Figure 6. The solution of the dispersion equation (10) for TE-modes for $\varepsilon = 1$, $\varepsilon_d = 1$, $\mu_d = 1$, $\Delta = 0.8$. The curves marked by the numbers 1 and 2 corresponds to the two eigenmodes of waveguide structure.

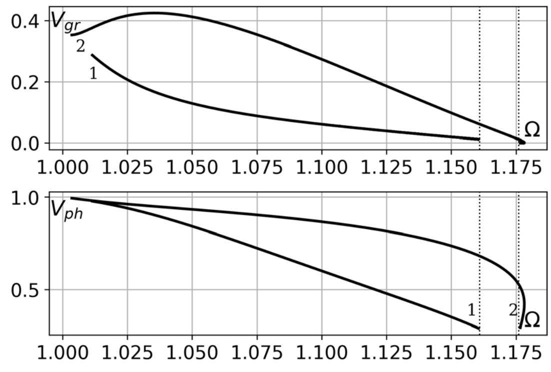

Figure 7. The group V_{gr} and phase V_{ph} normalized velocities of TE modes presented on the Figure 6. The parameters set and curve numbering are the same as for the Figure 6

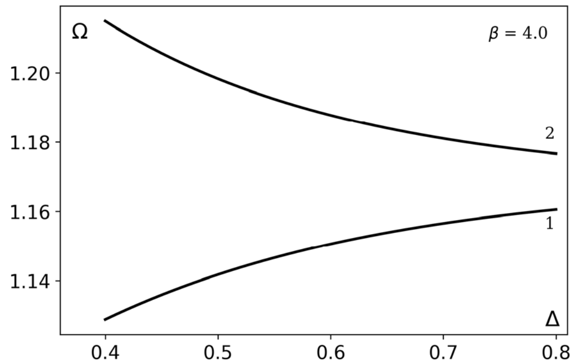

Figure 8. The variation of the normalized wave eigen frequency Ω obtained due to the solution of the dispersion equation (10) when $\varepsilon = 1$, $\varepsilon_d = 1$, $\mu_d = 1$ for $\beta = 4$.

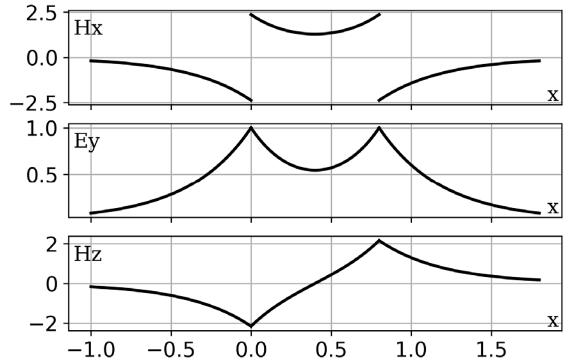

Figure 9. The wave field components normalized on the $E_y(0)$ for the mode 2 in the Fig. 6. The parameters set are the same as was used for the Fig. 6. The wave field structure is calculated for the region when $V_{gr} \sim 0$ ($\beta \approx 2.804$, $\Omega \approx 1.178$).

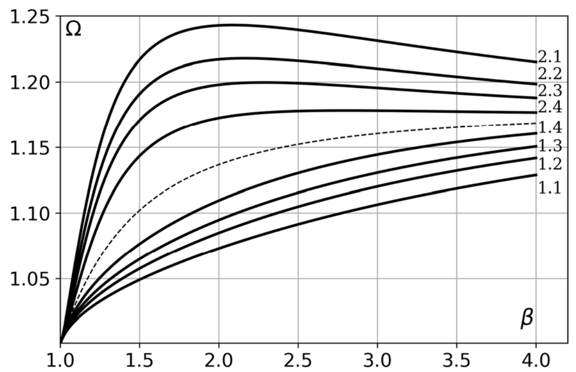

Figure 10. The solution of the dispersion equation (10) for TE-modes for $\varepsilon = 1$, $\varepsilon_d = 1$, $\mu_d = 1$. The curves marked by the numbers 1 and 2 before point corresponds to the two eigenmodes of waveguide structure. The numbers after the point corresponds to different Δ value: 1 – 0.4, 2 – 0.5, 3 - 0.6, 4 – 0.8. Dashed curve corresponds to the eigen wave of the simplified model, presented in [12].

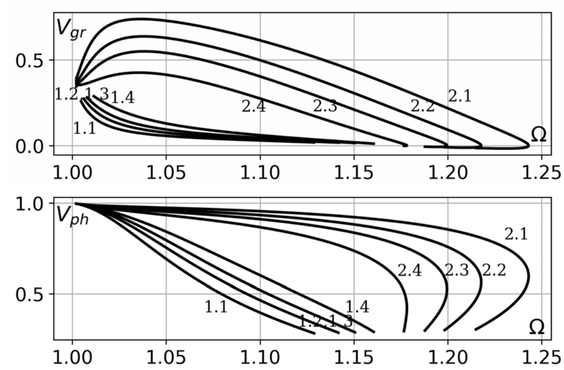

Figure 11. The group V_{gr} and phase V_{ph} normalized velocities of TE-modes presented on the Figure 10. The parameters set and curve numbering are the same as for the Figure 10.

The dependence of the normalized frequency Ω of the eigen TE waves of the considered structure versus normalized wavenumber β for $\varepsilon=1$, $\varepsilon_d=1$, $\mu_d=1$. The curves marked by the numbers 1 and 2 before point corresponds to the first and second eigenwaves of waveguide structure. The numbers after the point corresponds to different Δ value: $1 - \Delta=0.4$, $2 - \Delta=0.5$, $3 - \Delta=0.6$, $4 - \Delta=0.8$. Dashed curve corresponds to the eigen wave of the simplified model, presented in [12]. It is shown, how gradually increase of metamaterial slab thickness leads to the appropriate convergence of two eigen modes of the considered waveguide structure to the eigen wave of the simplified model, presented in [12] for the same parameter set. It is necessary to mention the possibility of the effective control of the frequency ranges where two or only one eigen mode of the considered waveguide structure exist due to the appropriative choice of the metamaterial slab thickness.

The dependence of the group V_{gr} and phase V_{ph} normalized velocities for two eigen TE-modes versus the normalized frequency Ω for the same parameter set as for the Fig. 10 is presented in the Fig. 11.

The numbering of the curve is the same as for the Fig. 10. It is shown that due to variation of the metamaterial slab thickness it is possible to manage of the frequency region size where the mode that propagates along the considered structure is single and possess the negative group velocity.

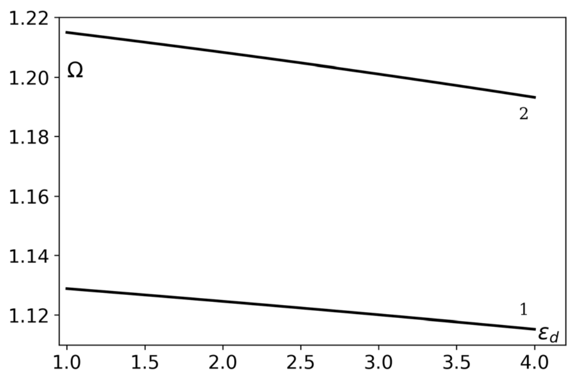

Figure 12. The dependence of the eigen TE wave normalized frequency Ω when $\varepsilon=1$, $\mu_d=1$, $\Delta=0.4$ for $\beta=4$ versus the ε_d value

The dependence of the obtained solutions of the dispersion equation (10) upon the permittivity constant of ordinary dielectric ε_d for the following parameter set $\varepsilon=1$, $\mu_d=1$, $\Delta=0.4$ and for $\beta=4$ is presented at the Fig. 12. It is obtained that the increase of the ε_d parameter leads to the slight decrease of the wave frequency Ω for both modes.

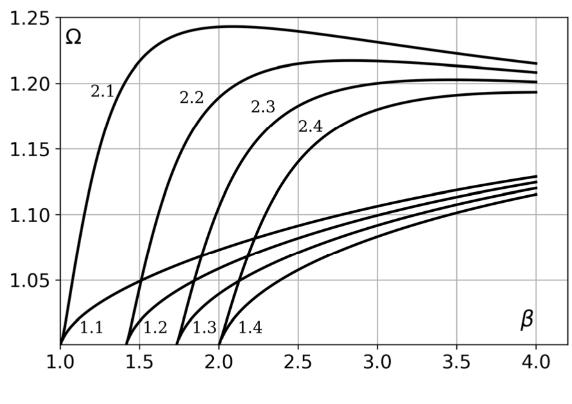

Figure 13. The solution of the dispersion equation (10) for TE-modes for $\varepsilon=1$, $\mu_d=1$, $\Delta=0.4$. The curves marked by the numbers 1 and 2 before point corresponds to the two eigenmodes of waveguide structure. The numbers after the point corresponds to different ε_d value.

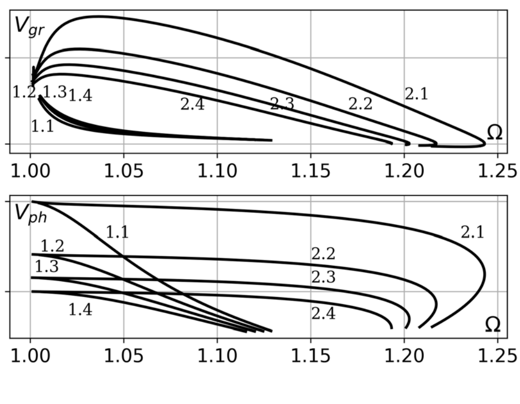

Figure 14. The group V_{gr} and phase V_{ph} normalized velocities of TE modes presented on the Figure 13. The parameters set and curve numbering are the same as for the Figure 13.

The detailed analysis of the impact of the ε_d parameter on the dispersion properties of the TE eigen waves on the waveguide considered is presented in Fig. 13. The calculations were made for the following problem parameter set: $\varepsilon=1$, $\mu_d=1$, $\Delta=0.4$. The curves marked by the numbers 1 and 2 before the point corresponds to the first and second eigenwaves of waveguide structure. The numbers after the point corresponds to solutions for different ε_d value:

1 - $\varepsilon_d = 1$, $2 - \varepsilon_d = 2$, $3 - \varepsilon_d = 3$, $4 - \varepsilon_d = 4$. It is shown, that the increase of the ε_d value results to the decrease and even to the disappearance of the third, most high-frequency region of the frequency interval. At the same time the first and the second frequency regions, where two eigen TE modes and one eigen TE mode waveguide structure can exist, respectively, stay almost unchangeable. Also, the increase of the ε_d value leads to the essential decrease of the maximum value of the wavelength of the surface modes that can propagate in this structure (see Fig. 13).

The dependence of the group V_{gr} and phase V_{ph} velocities for two eigen TE-modes versus the normalized frequency Ω for the same parameter set as for the Fig. 13 is presented in the Fig. 14. The numbering of the curve is the same as for the Fig. 13. It is shown, that changing the ε_d parameter value leads to the substantial decrease of phase and group velocities of the mode 2 and of the phase velocity of mode 1 (Fig. 14). The group velocity of the mode 1 remains practically unchanged. It is necessary to mention that due to changing ε_d value one can effectively control the size of the frequency region where the single mode 2 possesses negative group velocity (see Fig. 14).

CONCLUSION

It was studied the peculiarities of propagation of slow surface electromagnetic waves directed along the flat mu-negative lossless metamaterial slab surrounded by the ordinary dielectric material. It was found that two electromagnetic surface modes of TE can propagate at the interface between the mu-negative metamaterial layer and a conventional dielectric. It was studied the dispersion properties, spatial distribution of electric and magnetic field amplitudes of these eigenwaves of the considered structure for different problem parameters. It is necessary to mention the existence of new mode, as compared with previously studied simplified model [9]. This new mode can propagate in one mode regime and possesses the frequency range where its group velocity has a negative value. It was found that due to variation or metamaterial slab thickness, or ε_d parameter value one can effectively control the size of the frequency region where this single mode possesses negative group velocity. The obtained results can be useful for both modeling and manufacturing of modern devices based on metamaterials.

This work was supported by the Ministry of Education and Science of Ukraine, under the Projects 22-13-20 and 2-13-21.

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ПОВІЛЬНІ ПОВЕРХНЕВІ ВЛАСНІ МОДИ, ЩО ПОШИРЮЮТЬСЯ ВЗДОВЖ ШАРУ МЮ-НЕГАТИВНОГО МЕТАМАТЕРІАЛУ

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У статті наведено результати дослідження повільних поверхневих електромагнітних хвиль, спрямованих уздовж плоскої мю-негативної пластини метаматеріалу, оточеної звичайним діелектричним матеріалом. Розглядається випадок ізотропного і однорідного метаматеріалу без втрат. Цей метаматеріал має додатню електричну та від'ємну магнітну проникності у певному діапазоні частот. Встановлено, що вздовж такої хвилевідної структури можуть поширюватися дві поверхневі моди ТЕ поляризації. Досліджено дисперсійні властивості, просторовий розподіл електромагнітного поля, а також фазові та групові швидкості цих повільних мод. Перша мода є звичайною прямою хвилею і має нижчу частоту та меншу фазову швидкість, ніж друга мода. Друга мода може мати нульову групову швидкість на певній частоті. Досліджено характеристики цих поверхневих мод для різних значень параметрів шару мю-негативного метаматеріалу. Досліджувані поверхневі електромагнітні хвилі можуть бути використані як в лабораторних експериментах, так і в різних технологіях.
Ключові слова: мю-негативний метаматеріал; електромагнітна поверхнева хвиля; дисперсійні властивості хвилі; просторова структура моди