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SLOW SURFACE ELECTROMAGNETIC WAVES AT THE METASURFACE / DISSIPATIVE DIELECTRIC INTERFACE

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The possibilities of the slow surface electromagnetic waves propagation along the flat boundary of a metasurface with a dissipative dielectric are studied. The metasurface is a thin flat slab of metamaterial with simultaneously negative permittivity and permeability with "amplification". All media were assumed to be isotropic. Dispersion dependences are obtained for the eigenmodes of such a waveguide structure. The possibility of full compensation of the energy losses of surface waves by the appropriate choice of the “gains” values is demonstrated.

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INTRODUCTION

The noteworthy progress was made in the manufacturing of metasurface [1, 2] based on the metamaterials [3] during the last years. The metamaterials are composite materials consisting of cells that play the role of atoms for electromagnetic disturbances, the wavelength of which is much larger than the cell’s size.

For these artificial “substances” it is possible to get such combination of electromagnetic characteristics which so far unknown for natural substances.

In particular, it can manage to achieve simultaneously negative value of permittivity and permeability. Such double negative metamaterials (DNM) are often referred as left-handed materials or negative refractive media.

In our previous paper [4] it was demonstrated the full loss compensation for the surface electromagnetic wave that propagates in plane waveguide structure along the interface between the thin layer of the high-permittivity dielectric with strong losses and the isotropic DNM material with gain.

The aim of this work is to determine the possibility of propagation of the plane slow surface electromagnetic waves in the plane structure consisting of the metasurface and the dissipative dielectric. The task geometry has shown in Fig. 1.

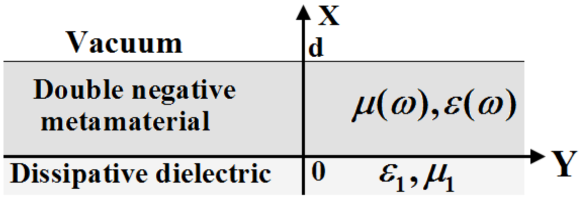

Fig. 1. The geometry of problem

A dissipative dielectric (DD) possesses the moderate value of power losses. The metasurface we call the one side of a thin flat slab of the metamaterial with "gain" and simultaneously negative both dielectric permittivity and magnetic permeability. At another side, this metamaterial layer is adjacent to dissipative dielectric material. Similarly to our previous paper [4] it was assumed the existence of the gains in the metamaterial to compensate the wave energy losses and is not discussed mechanisms of such gains [3].

1. TASK SETTINGS

We investigate the electromagnetic waves propagating along a plane waveguide structure in the Z - axis direction. Let the X - axis been perpendicular to the interface. The semi-infinite region $x \le 0$ is occupied by dissipative dielectric without dispersion, but with losses described with help the imaginary part of the permittivity $\varepsilon_1 = 4 + 0.05i$, $\mu_1 = 1$.

The gap $0 \le x \le d$ is filled by metamaterial that characterized by the commonly used the effective permittivity $\varepsilon(\omega)$ and permeability $\mu(\omega)$ [5]:

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

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

Throughout it was considered the metamaterial with $\omega_p / 2\pi = 10$ GHz, $\omega_0 / 2\pi = 4$ GHz, and $F = 0.56$ [5] with thickness $d = 0.716$ cm, so $\Delta = \omega_0 d / c = 0.6$.

Such choice of the metamaterial parameters leads to the appearance of the frequency interval $1 < \Omega = \omega/\omega_0 < 1.5$ where $\varepsilon(\omega) < 0$ and $\mu(\omega) < 0$ simultaneously (DNM). The values of ν_G, γ_G are entered for modelling the “electric and magnetic gains” of electromagnetic waves in the metamaterial.

The semi-infinite region $x \ge d$ is occupied by the air or vacuum without both dispersion and losses with constant permittivity $\varepsilon_2 = 1$ and permeability $\mu_2 = 1$.

We will consider the slow surface electromagnetic wave that can propagate in this structure. We will find the solutions for the plane wave disturbances that decreasing exponentially far away from the boundaries. The spatial-temporal dependence of the wave components has such a form:

$$E, H \propto E(x), H(x) \exp[i(k_3 z - \omega t)]. \qquad (3)$$

Here the amplitudes of the wave fields decrease exponentially from the boundaries, axis Z lies at the separation plane, and x is the coordinate perpendicular to the wave propagation direction and $k_3 = \mathrm{Re}(k_3) + i \cdot \mathrm{Im}(k_3)$.

Just like [5] it is possible to split the Maxwell equations on two independent sub-systems. One of them describes the waves of H-type that contain (H_x, E_y, H_z) – components, and another – waves of E-type that contain (E_x, H_y, E_z) – components.

The dispersion equation for E-type mode of structure considered has the form:

$$\begin{aligned}&\varepsilon(\omega)\kappa(\varepsilon_1 h_2 + \varepsilon_2 h_1)\cosh[\kappa d] + \\ &(h_1 h_2 \varepsilon^2(\omega) + \varepsilon_1\varepsilon_2\kappa^2)\sinh[\kappa d] = 0,\end{aligned} \qquad (4)$$

where $h_{1,2} = \sqrt{k_3^2 - \varepsilon_{1,2}\mu_{1,2}k^2}$, $\kappa = \sqrt{k_3^2 - \varepsilon(\omega)\mu(\omega)k^2}$ - are the transverse wave vectors, $k = \omega / c$, were c is the light speed.

The wave of H-type possesses the dispersion relation of the similar form:

$$\begin{aligned}&\mu(\omega)\kappa(\mu_1 h_2 + \mu_2 h_1)\cosh[\kappa d] + \\ &(h_1 h_2 \mu^2(\omega) + \mu_1\mu_2\kappa^2)\sinh[\kappa d] = 0.\end{aligned} \qquad (5)$$

2. MAIN RESULTS

Two dispersion equations (4), (5) were solved numerically. From the beginning these equations was solved for ideal structure: both losses and gains were assumed to be zero (Fig. 2). The inclined line Q and curve S correspond to the conditions $h_1 = 0$ and $\kappa = 0$, respectively. They separate the region, where the amplitudes of the wave fields decrease exponentially from the boundaries. So the slow surface electromagnetic waves can exist in that region of Figs. 2, 3. Three solutions have been obtained of the dispersion equations (4), (5): one solution for E – wave and two solutions for H – waves.

Curves H1-wave, H2-wave correspond to the waves of H-type and the curve E-wave corresponds to wave of E-type.

Let’s introduce such dimensionless quantities: the frequency $\Omega = \omega / \omega_0$, the wavenumber $\beta = \mathrm{Re}(k_3)c / \omega_0$, the decrement $\alpha = \mathrm{Im}(k_3)c / \omega_0$, the “electric” $\nu = \nu_G / \omega_0$ and “magnetic” gains $\gamma = \gamma_G / \omega_0$.

The considered E-wave and H2-wave are forward (both phase and group velocities are positive) and H1-wave is backward (phase velocity is positive and group velocity is negative).

It can be argued that the losses do not put an appreciable changes the dispersion dependences of the considered waves (see Figs. 2, 3)

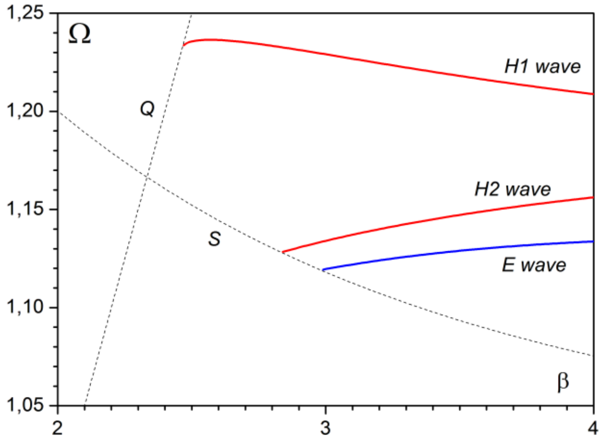

Fig. 2. The dependence of the normalized frequency Ω on the wavenumber β for the metamaterial layer with zero gains $\gamma_G = \nu_G = 0$ and for non-dissipative dielectric with $\varepsilon_1 = 4$

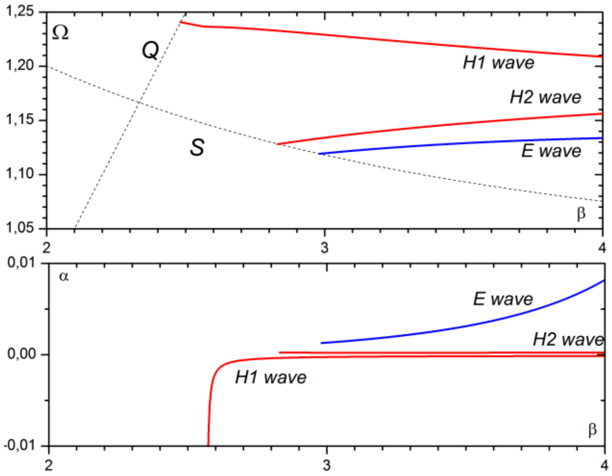

Fig. 3. The dependence of the frequency Ω and decrement α on the wavenumber β for the metamaterial gains values $\gamma = \nu = 0$, and for dissipative dielectric: $\varepsilon_1 = 4 + 0.001i$

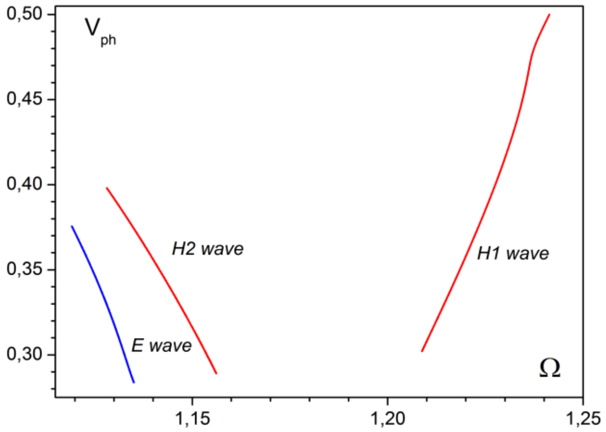

Fig. 4. The normalized phase velocity $V_{ph} = \omega / ck_3$ versus normalized frequency Ω

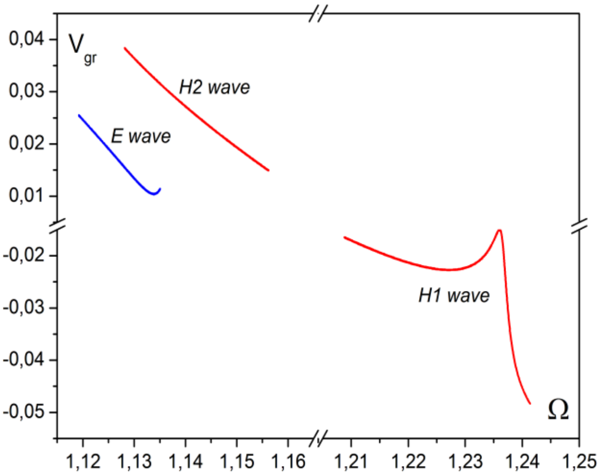

Fig. 5. The normalized group velocity $V_{gr} = c^{-1} d\omega / dk_3$ *versus normalized frequency* Ω

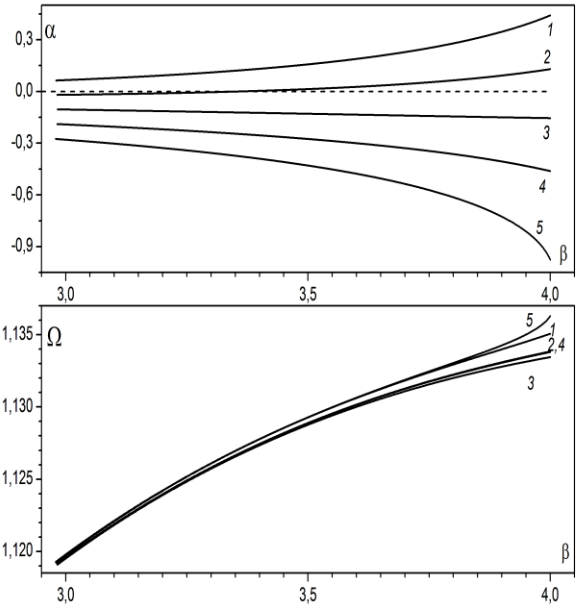

Fig. 6. The dependence of the normalized decrement α *and the frequency* Ω *of the E wave versus normalized wavenumber* β *for different values of "magnetic" gain* $\gamma = (1-0.0; 2-0.005; 3-0.01; 4\ -0.015;$ *5 – 0.02 for* $\varepsilon_1 = 4+0.05i$ *and* $\nu = 0$

According to Fig. 4 the phase velocities of modes considered in 2...3 times less then the light speed. The group velocity of the forward modes decrease with increasing frequency, but increases for the backward mode H1 (Fig. 5).

The Figs. 6-11 illustrate the separate influences of the DNM "electric and magnetic gains" on the dependencies of the decrements and the mode frequencies versus wavenumber in the presence of dielectric's dissipation.

It's remarkable that the influence of "electric and magnetic gains" on the modes dispersive curves is rather weak. At the same time, the influence of "electric and magnetic amplification" on the values of the damping decrements of the modes under consideration is significant.

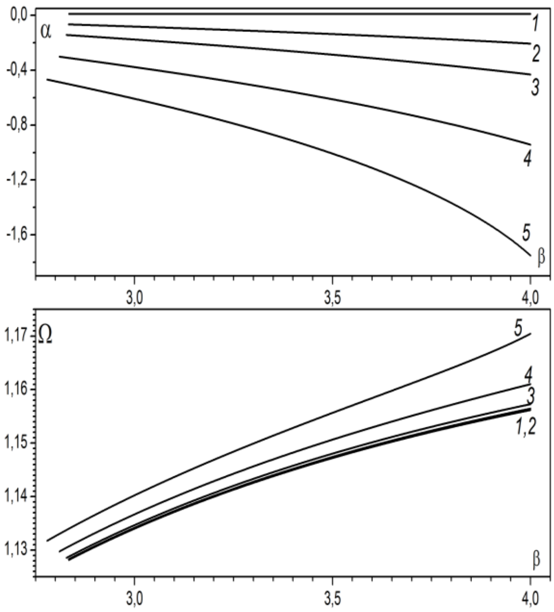

Fig. 7. The dependence of the decrement α *and the frequency* Ω *of the H2-wave versus wavenumber* β *for different values of "magnetic" gain* $\gamma = (1-0.0;\ 2-0.01;\ 3-0.02; 4-0.03; 5-0.05)$ *for* $\varepsilon_1 = 4+0.05i$ *and* $\nu = 0$

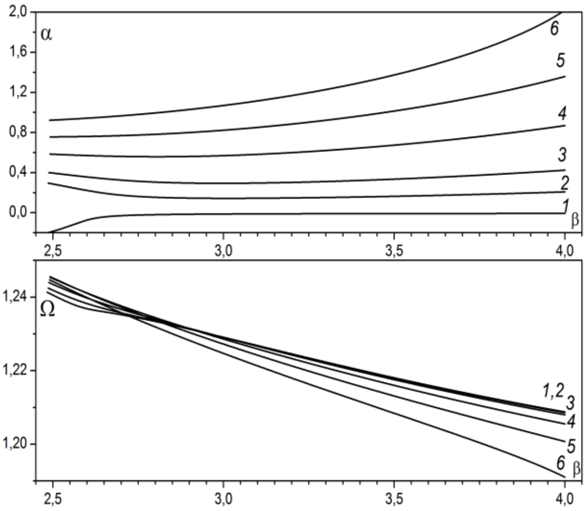

Fig. 8. The dependence of the normalized decrement α *and the frequency* Ω *of the H1-wave versus normalized wavenumber* β *under different values of "magnetic" gain* $\gamma = (1-0.0; 2-0.005; 3-0.01;\ \ 4-0.02;\ \ 5-0.03;\ \ 6-0.04)$ *for* $\varepsilon_1 = 4+0.05i$ *and* $\nu = 0$

The type of influence of "electric and magnetic gains" on the damping decrements is enough different. That's why we represent all of them.

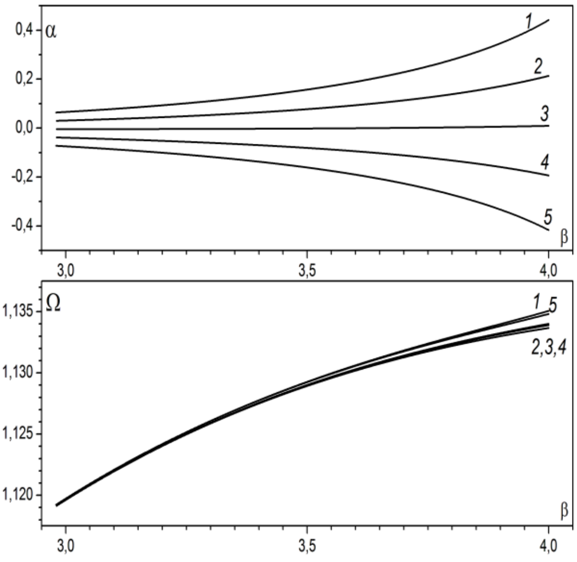

Fig. 9. The dependence of the decrement α and the mode frequency Ω of the E-wave versus wavenumber β for different values of "electric" gain

$\nu = (1-0.0; 2-0.005; 3-\ 0.01; 4-0.015; 5-0.02)$ *for*

$\varepsilon_1 = 4+0.05i$ *and* $\gamma = 0$

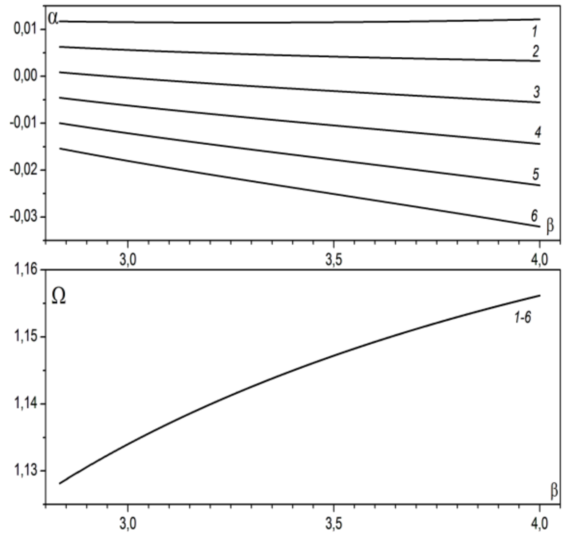

Fig. 10. The dependence of the normalized decrement α and the mode frequency Ω of the H2-wave versus wavenumber β for different values of "electric" gain

$\nu = (1-0.0; 2-0.01; 3-\ 0.02; 4-0.03; 5-0.04;$

$6-0.05)$ *for* $\varepsilon_1 = 4+0.05i$ *and* $\gamma = 0$

The Figs. 12-17 present the full compensation ($\alpha = 0$) for set of the system parameters for three modes.

We figure out that condition of full dissipative compensation $\alpha = 0$ is reachable for each of the three modes. We see that both the "magnetic" and "electric gains" can to compensate the losses for the all considered modes.

We have established a rather unexpected fact. It turned out that it is possible to compensate the dielectric losses for each mode with the help of only one non-zero "gain" at a zero value of the other "gain".

Thus, such full compensations (for a given $\beta = 4.0$) are possible:

for the E-wave:

a) $\nu = 0$, $\gamma \approx 0.007$; b) $\gamma = 0$, $\nu \approx 0.01$;

for H2-wave:

a) $\nu = 0$, $\gamma \approx 0.0003$; b) $\gamma = 0$, and $\nu \approx 0.015$;

for H1-wave:

a) $\nu = 0$, $\gamma \approx 0.00015$; b) $\gamma = 0$, and $\nu \approx 0.005$.

It was shown, that the gain values needed for the full compensation of the electromagnetic surface waves energy losses in the dissipative dielectric are quite reasonable.

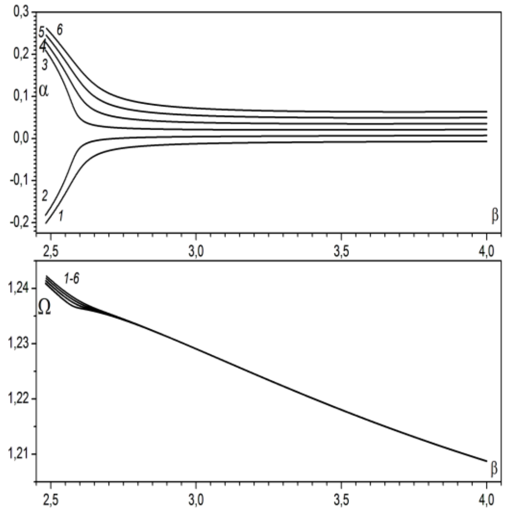

Fig. 11. The dependence of the normalized decrement α and the mode frequency Ω of the H1-wave versus wavenumber β for different values of "electric" gain

$\nu = (1-0.0; 2-0.01;\ \ 3-0.02; 4-0.03;\ \ 5-0.04;$

$6-0.05)$ *for* $\varepsilon_1 = 4+0.05i$ *and* $\gamma = 0$

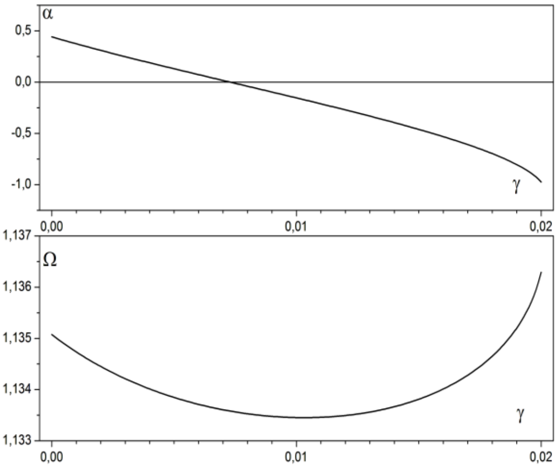

Fig. 12. The dependences of the of the decrement α and the mode frequency Ω of E-wave on the value of gain γ if $\nu = 0$ for $\beta = 4.0$

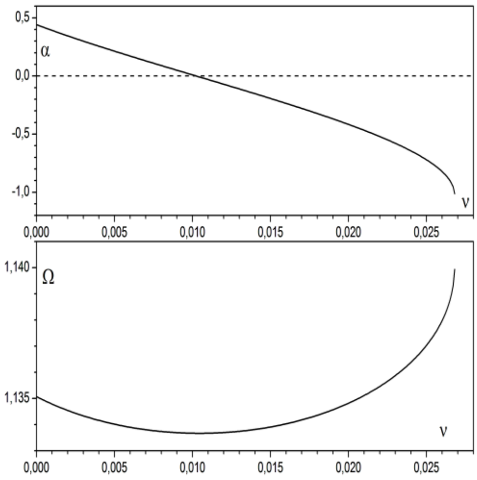

Fig. 13. The dependences of the decrement α and the mode frequency Ω of E-wave on the value of gain ν if $\gamma = 0$ for $\beta = 4.0$

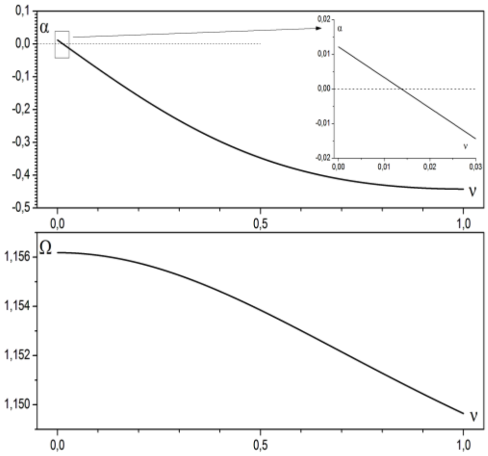

Fig. 14. The dependences of the decrement α and the mode frequency Ω of H2-wave on the value of gain ν if $\gamma = 0$ for $\beta = 4.0$

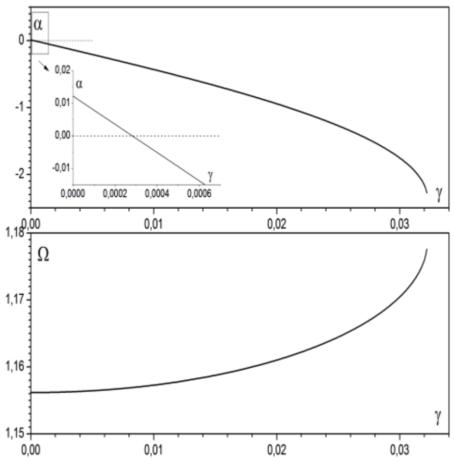

Fig. 15. The dependences of the of the decrement α and the mode frequency Ω of H2-wave on the value of gain γ if $\nu = 0$ for $\beta = 4.0$

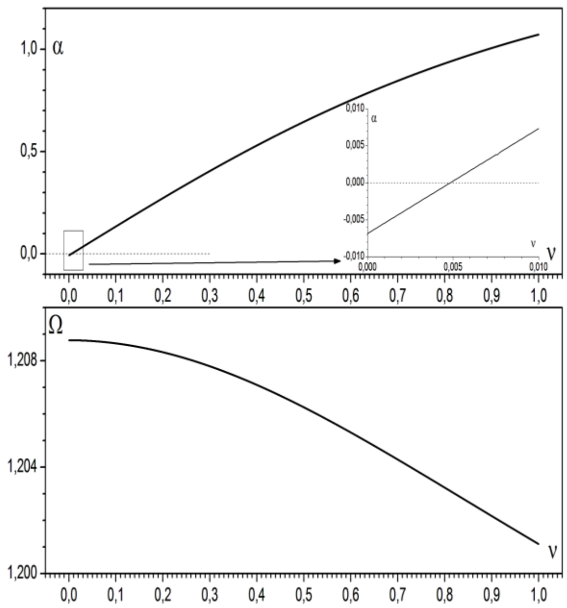

Fig. 16. The dependences of the of the decrement α and the mode frequency Ω of H1-wave on the value of gain ν if $\gamma = 0$ for $\beta = 4.0$

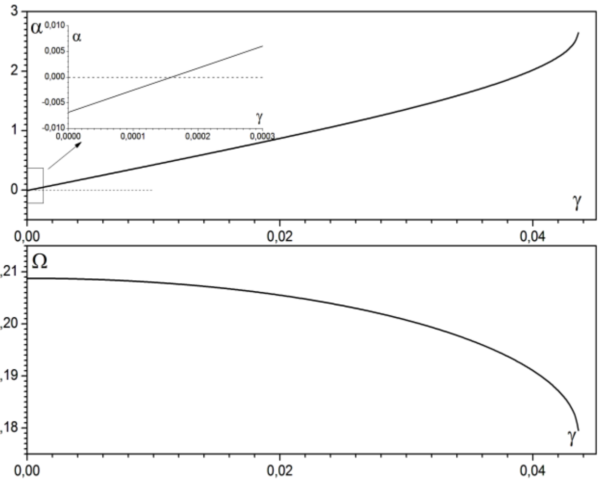

Fig. 17. The dependences of the decrement α and the mode frequency Ω of H1-wave on the value of gain γ if $\nu = 0$ for $\beta = 4.0$

CONCLUSIONS

It was obtained that slow surface electromagnetic waves can be sustained by boundary between metasurface and dissipative dielectrics. The loss of wave energy is compensated by the use of the metamaterials with "gains".

The results obtained in this work can be useful for the various practical applications of metamaterials in technology, life science, and medicine.

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МЕДЛЕННЫЕ ПОВЕРХНОСТНЫЕ ЭЛЕКТРОМАГНИТНЫЕ ВОЛНЫ НА ГРАНИЦЕ РАЗДЕЛА МЕТАПОВЕРХНОСТЬ / ДИССИПАТИВНЫЙ ДИЭЛЕКТРИК

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

Изучены свойства медленных поверхностных электромагнитных волн, распространяющихся вдоль плоской границы метаповерхности с диссипативным диэлектриком. Метаповерхность представляет собой узкий плоский слой метаматериала с одновременно отрицательными диэлектрической и магнитной проницательностями с «усилением». Все среды считались изотропными. Получены дисперсионные зависимости для собственных мод такой волноводной структуры. Продемонстрирована возможность полной компенсации потерь энергии поверхностных волн соответствующим выбором значений «усилений».

ПОВІЛЬНІ ПОВЕРХНЕВІ ЕЛЕКТРОМАГНІТНІ ХВИЛІ НА МЕЖІ ПОДІЛУ МЕТАПОВЕРХНЯ / ДИСИПАТИВНИЙ ДІЕЛЕКТРИК

В.К. Галайдич, О.Є. Споров, В.П. Олефір, М.О. Азарєнков

Вивчено властивості повільних поверхневих електромагнітних хвиль, що поширюються уздовж плоскої межі метаповерхні з дисипативним діелектриком. Метаповерхня є вузький плоский шар метаматеріалу з негативними як діелектричною, так і магнітною проникливостями з «підсиленням». Усі середовища вважались ізотропними. Отримано дисперсійні залежності власних мод такої хвилеводної структури. Продемонстровано можливість повної компенсації втрат енергії поверхневих хвиль відповідним вибором значень «підсилень».