SURFACE ELECTROMAGNETIC WAVES ON BOUNDARY BETWEEN LOSSY DIELECTRIC AND LEFT-HANDED MATERIAL WITH GAIN

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It was studied the properties of surface electromagnetic waves that propagate along the interface between the semi-infinite lossy dielectric medium and the left-handed material with "gain". It was assumed that both media are isotropic. The dispersion curves of the eigenmodes of such waveguide structures were obtained. It was shown that for the different modes of waveguide structure there are different quantities and ratios of left-handed material with "gain" required to compensate for wave energy losses in the dielectric.

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INTRODUCTION

Till now mankind has been achieved a great progress in the experimental and theoretical research of new artificial materials (so called metamaterials). These metamaterials demonstrate interesting behavior and possess a number of unusual physical properties that do not exist in all natural substances. Such unique properties give the opportunity to create a lot of innovative devices. The characteristic feature of the metamaterials is the fact, that the electric field vector, the magnetic field vector and wavevector of the electromagnetic waves in such media form a left-handed system (so, such metamaterials are often called "left-handed materials", LHM) [1].

It is well known that the undamped surface electromagnetic waves can propagate along boundary between lossless LHM and lossless dielectric [2, 3]. The amplitude of these waves will decrease with propagation distance if we take into account the losses in the dielectric. Moreover, losses in metamaterials take place due to Joule heating in metallic elements of these metamaterials [4]. Let us assume the existence of gain in the LHM to compensate the wave losses [5, 6].

1. TASK SETTINGS

The considered electromagnetic wave propagates along the planar waveguide interface that separates the lossy dielectric medium and the left-handed material. Both media was assumed be isotropic. Using of the metallic elements in metamaterials leads to the considerable electromagnetic waves spatial damping due to the well known Joule heating. The left-handed material will be characterized by effective permittivity $\varepsilon(\omega)$ and permeability $\mu(\omega)$ that depend on the wave frequency and commonly expressed with the help of experimentally obtained expressions [2]:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega - i\nu)},$$
$$\mu(\omega) = 1 - \frac{F\omega^2}{\omega(\omega - i\gamma) - \omega_0^2}, \qquad (1)$$

here ω_p is effective plasma frequency, ω_0 is the characteristic frequency of LHM. In further study it was considered the LHM with $\omega_p / 2\pi = 10$ GHz and $\omega_0 / 2\pi = 4$ GHz and parameter $F = 0.56$ [5].

Such parameters ratio leads to the existence of the frequency region where $\varepsilon(\omega) < 0$ and $\mu(\omega) < 0$ simultaneously. The model parameters ν, γ simulate the "electric" and "magnetic" gain of electromagnetic waves in the metamaterial, respectively.

We will assume that dielectric medium is a nonmagnetic ($\mu_D = 1$) and posses the only "electric" losses with constant dielectric permittivity $\varepsilon_D = \varepsilon_D^{'} + \varepsilon_D^{''} = 1 + i \cdot 0.01$.

Let us consider the electromagnetic wave that propagates along this structure. It was assumed that the wave disturbances exponentially tend to zero ($\propto \exp[-h_D |x|], \exp[-\kappa |x|]$) far away from boundary between two media. The dependence of the wave components on time t and coordinates x and z is expressed the following form:

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

here z lies at the separation plane, and x is the coordinate rectangular to the wave propagation direction and $k_3 = \mathrm{Re}(k_3) + i \cdot \alpha$.

In our case it's possible to split the system of Maxwell equations on two sub-systems. One of them describes the waves of H- type and another – waves of E-type.

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

$$\varepsilon(\omega) \cdot h_D(k_3, \omega) + \varepsilon_D \cdot \kappa(k_3, \omega) = 0, \qquad (3)$$

here $h_D = \sqrt{k_3^2 - \varepsilon_D \mu_D k^2}$, $\kappa = \sqrt{k_3^2 - \varepsilon(\omega)\mu(\omega) k^2}$, transverse wave vectors of appropriative exponents, $k = \omega / c$, were c is the speed of light in vacuum.

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

$$\mu(\omega)\cdot h_D(k_3,\omega)+\mu_D\cdot\kappa(k_3,\omega)=0. \qquad (4)$$

2. MAIN RESULTS

The results of numerical calculation of dispersion equations for *E*- and *H*- waves for the selected set of parameters are shown at Fig. 1. There are three solutions of two dispersion equations (3, 4).

Curves *E1*, *E2* correspond to the waves of *E*- type and curve *H* corresponds to wave of *H*-type. For the chosen set of parameters the domain where the metamaterial demonstrates left-handed properties (simultaneously $\varepsilon(\omega)<0$ and $\mu(\omega)<0$) lies in the region where $1<\Omega<1.5$. The inclined straight line corresponds to $\xi=\Omega\sqrt{\varepsilon_D}$ ($\xi=\Omega\sqrt{\varepsilon_D}$), that practically coincides with "light" line $\xi=\Omega$. The curve $\xi=\Omega\sqrt{\varepsilon(\omega)\mu(\omega)}$ corresponds to the condition $\kappa(k_3,\omega)=0$ and separates region, where surface electromagnetic wave can exist.

The modes considered are both forward and backward: modes *E1*, *E2* are forward waves, i.e. both phase and group velocities are positive, but *H*- mode is backward, in which phase velocity is positive and group velocity is negative. The absolute value of the group velocity of *H*- waves can be very low for short waves.

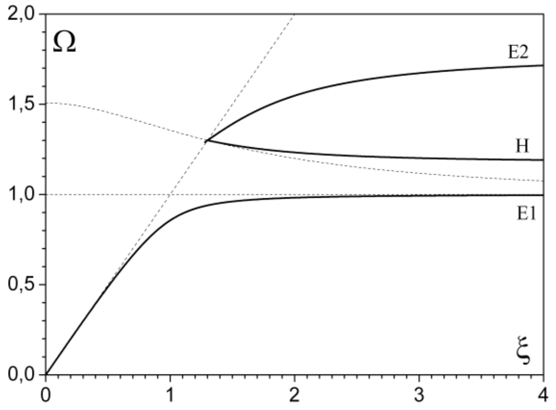

Fig. 1. The dependence of the frequency $\Omega=\omega/\omega_0$ on the wavenumber $\xi=k_3c/\omega_0$ for left-handed material gain values $\gamma=10^{-3}$ and $\nu=10^{-3}$

Figs. 2-7 presents the dependence of the imaginary part of wave number α on the normalized wavenumber for different values of "electric" and "magnetic" gains of the left-handed material.

For the *E1*-mode for the long wavelengths ($\xi\le1.7$) the damping takes place for all values of gain considered, but for short wavelengths ($\xi>1.7$) amplitude of *E1*-mode will increase along the direction of propagation (see Fig. 3, 5).

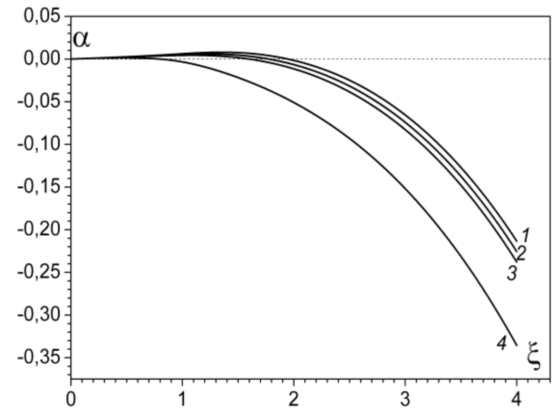

Fig. 2. The dependence of the imaginary part of wave number of E1-wave on of the wavenumber for different left-handed material gain values $\gamma=10^{-3}$ and $\nu=0$ (1); 0.005 (2); 10^{-2} (3); 0.05 (4)

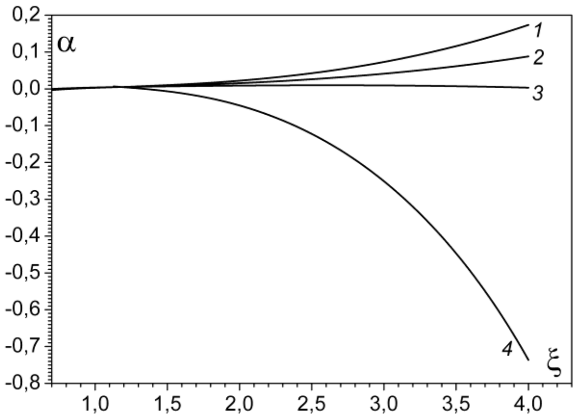

Fig. 3. The dependence of the imaginary part of wave number of E2-wave on the wavenumber for different left-handed material gain values $\gamma=10^{-3}$ and $\nu=0$ (1); 0.005 (2); 10^{-2} (3); 0.05 (4)

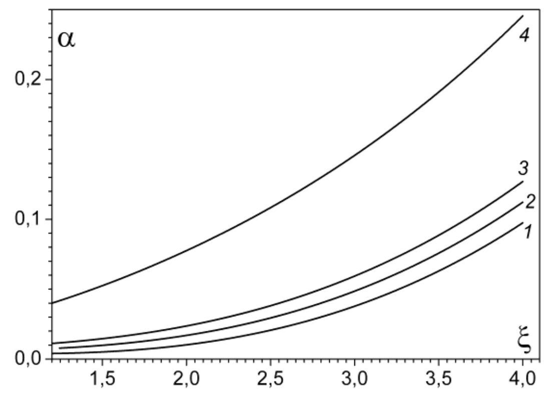

Fig. 4. The dependence of the imaginary part of wave number of H-wave on of the wavenumber for different left-handed material gain values $\gamma=10^{-3}$ and $\nu=0$ (1); 0.005 (2); 10^{-2} (3); 0.05 (4)

For the *E2*-mode the small values of gain do not give increasing; at value $\nu = 10^{-2}$ we have full loss compensation and at $\nu > 10^{-2}$ the increasing along propagation will take place.

The preliminary estimation of the media/waves parameters ratio give a conditions needed for full compensation of the dielectric losses $|\nu/\varepsilon(\omega)| \approx |\gamma/\mu(\omega)| \approx |\varepsilon''_D/\varepsilon'_D|$.

This estimation is fully confirmed for *E2*-mode both for long and short wavelengths. For *E2*-mode it is possible to compensate the dielectric losses by weak gain in the LHM medium (Figs. 3, 6).

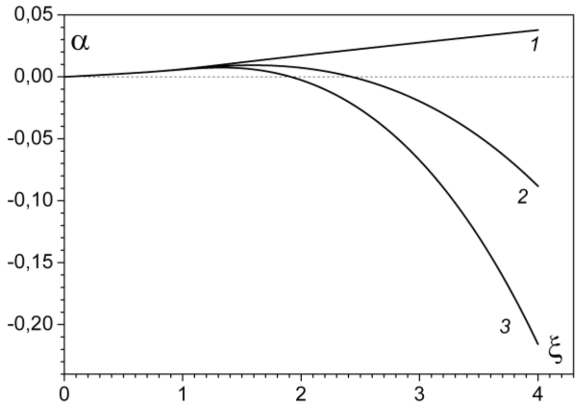

Fig. 5. The dependence of the imaginary part of wave number of E1-wave on of the wavenumber for different left-handed material gain values $\nu = 10^{-3}$ and
$\gamma = 0\,(1);\ 0.0005\,(2);\ 10^{-3}(3)$

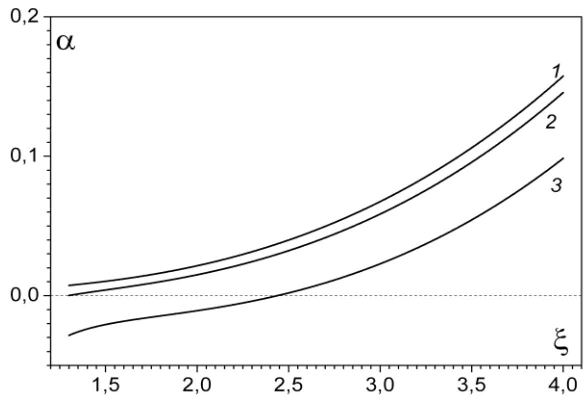

Fig. 6. The dependence of the imaginary part of wave number of E2-wave on of the wavenumber for different left-handed material gain values $\nu = 10^{-3}$ and
$\gamma = 0\,(1);\ 0.01\,(2);\ 0.05\,(3)$

As we can see from Fig. 4, 7, the compensation for *H*-mode is not successful under the considered values of the LHM gains.

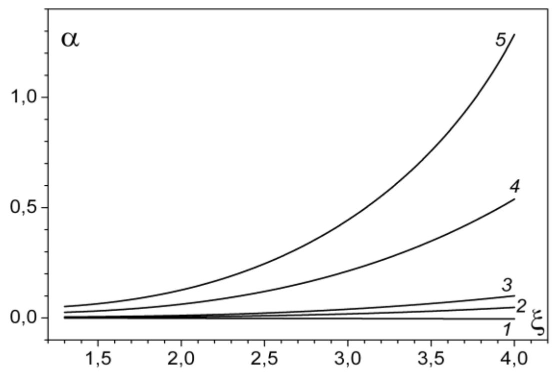

Fig. 7. The dependence of the imaginary part of wave number of H-wave on of the wavenumber for different left-handed material gain values $\nu = 10^{-3}$ and
$\gamma = 0\,(1);\ 0.0005\,(2);\ 10^{-3}(3)\,;\ 0.005\,(4);\ 10^{-2}(5)$

CONCLUSIONS

We have obtained that influence of positive-valued gain in the metamaterial is *very* different for the damping of different modes. To compensate the losses in dielectric medium it is need to choose different values of metamaterial's gain for the specific propagating mode.

It was demonstrated the possibility of full loss compensation for the surface electromagnetic wave at the boundary between the dielectric with losses and the isotropic left handed material with gain.

The results obtained in this work can be useful for the diverse practical applications of metamaterials in science and technology.

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ПОВЕРХНОСТНЫЕ ЭЛЕКТРОМАГНИТНЫЕ ВОЛНЫ НА ГРАНИЦЕ РАЗДЕЛА ДИЭЛЕКТРИКА С ПОТЕРЯМИ И ЛЕВОСТОРОННЕГО МАТЕРИАЛА С УСИЛЕНИЕМ

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Изучены свойства поверхностных электромагнитных волн, распространяющихся вдоль границы раздела полубесконечных диэлектрика с потерями и левостороннего материала с «усилением». Предполагалось, что обе среды являются изотропными. Получены дисперсионные зависимости для собственных мод такой волноведущей структуры. Показано, что для различных рассматриваемых мод структуры существуют различные величины и соотношения «усиления» левосторонней среды, которые необходимы для компенсации потерь энергии волны в диэлектрике.

ПОВЕРХНЕВІ ЕЛЕКТРОМАГНІТНІ ХВИЛІ НА МЕЖІ РОЗДІЛУ ДІЕЛЕКТРИКА З ВТРАТАМИ І ЛІВОСТОРОННЬОГО МАТЕРІАЛУ З ПІДСИЛЕННЯМ

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Вивчено властивості поверхневих електромагнітних хвиль, що поширюються уздовж межі розділу напівнескінченних діелектрика з втратами і лівостороннього матеріалу з «підсиленням». Вважалось, що обидва середовища є ізотропними. Отримано дисперсійні залежності для власних мод такої хвилеводної структури. Показано, що для різних розглянутих мод структури існують різні величини та співвідношення «посилення» лівостороннього середовища, що необхідні для компенсації втрат енергії хвилі в діелектрику.