East European Journal of Physics. 4. 294–297 (2023)
DOI: 10.26565/2312-4334-2023-4-37 ISSN 2312-4334

SURFACE ELECTROMAGNETIC TE-WAVES TOTAL INTERNAL REFLECTION

Viktor Galaydych[a], **Mykola Azarenkov**[a,b]
[a] *V.N. Karazin Kharkiv National University, 4, Svoboda Sq., Kharkiv, 61022, Ukraine*
[b] *Institute of Solid State Physics, Materials Science and Technologies, National Science Center Kharkiv Institute of Physics and Technology, 1 Akademichna St, Kharkiv, 61108, Kharkiv, Ukraine.*
[*] *Corresponding Author e-mail: viktor.galaydych@gmail.com*

Received July, 13, 2023; revised September 15, 2023; accepted November 6, 2023

We have considered the refraction of surface electromagnetic waves (SEW) at the heterogeneous metasurface. The considered structure consists of three regions: mu-negative metamaterial, ordinary magnetic, and vacuum. The boundaries between considered media are planar. A phenomenological approach was used; media were assumed to be lossless and isotropic. In this paper, we show the possibility of total internal reflection effect for SEW of TE-polarization that can propagate along such heterogeneous metasurface. The value of the angle of total internal reflection decreases for higher frequency waves from the interval under consideration. The presented result may help design both research and industry complex systems.

Keywords: *mu-negative metamaterial; Metasurface; Electromagnetic surface wave; Total internal reflection*

PACS: 52.35g, 52.50.Dg

1. INTRODUCTION

Artificially created composite materials called metamaterials are intensively researched [1]–[4]. Great interest in metamaterials is caused by the presence of such combinations of the electrodynamic characteristics that are not found in natural materials. The study of surface electromagnetic waves in metamaterials began with work [5]. To date, many articles have been published that studied the properties of surface electromagnetic waves in the structures metamaterials involved [6]–[8]. Most of research deal with a double-negative media, i.e. both dielectric permittivity and magnetic permeability are negative.

But creating a metamaterial that only has a negative magnetic permeability is significantly easier [9]. Recently were published the papers [10]–[12] in which study the surface electromagnetic waves at the interface between mu-negative medium and ordinary mu-positive medium. Aim of present work is to determine how the transition from one interface between such media to another interface formed by a different pair of media will affect the propagation of such surface waves.

2. PROBLEM STATEMENT AND RESULTS

The geometry of the structure to be considered is as follows. The lower half-space ($Z < 0$) filled by the negative permeability medium (mu-negative medium). The upper half-space ($Z > 0$), in its turn, consists of two halves. One half ($Z > 0, X > 0$) is vacuum, another ($Z > 0, X < 0$) is filled with a conventional magnetic material (see Fig. 1). The plane surface electromagnetic waves propagates in the plane ($Z = 0$) along interface between the negative permeability medium and a conventional magnet. Its wave vector k_1 inclines to the normal to the plane ($X = 0$) at an angle θ_i. In addition to the reflection of this wave from the plane $X = 0$ separating the magnetic material from the vacuum, a refracted plane surface wave propagates in the half-space $X > 0$ along the plane interface 'the mu-negative medium/vacuum'. Its wave vector k_2 lies in the plane $X = 0$ and inclines to the normal at an angle θ_r.

Maxwell's equations admit solutions in the form of the surface wave disturbances (1–3) of TE-polarization, e.g. with an electric $\vec{E} = \{0; E_y; 0\}$ and magnetic fields $\vec{H} = \{H_x; 0; H_z\}$ [12]:

$$E_{y1,2} = E_{y01,2} \exp[-\kappa_{1,2}|z| + i(\vec{k}_{1,2}\vec{r} - \omega t)], \tag{1}$$

$$H_{z1,2} = (\frac{k_{1,2}}{k\mu_{1,2}})(\exp[-\kappa_{1,2}|z| + i(\vec{k}_{1,2}\vec{r} - \omega t)], \tag{2}$$

Cite as: V. Galaydych, M. Azarenkov, East Eur. J. Phys. 4, 294 (2023), https://doi.org/10.26565/2312-4334-2023-4-37

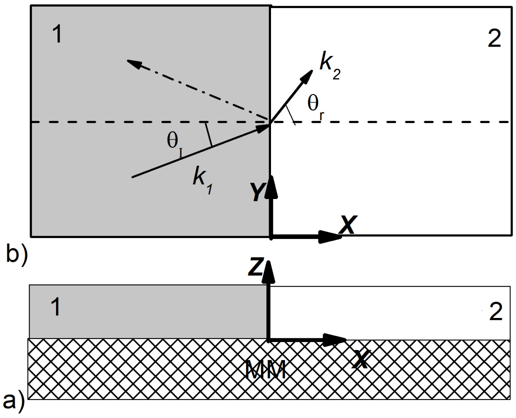

Figure 1. The geometry of structure: shaded – mu-negative metamaterial, grey – magnetic material, white – vacuum; a)-side view, b)-top view

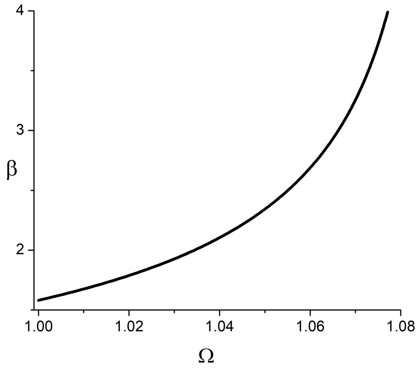

Figure 2. The normalized wavenumber versus the normalized frequency for surface electromagnetic TE-wave

$$H_{x1,2} = (-\frac{\kappa_{1,2}}{k\mu_{1,2}})(\exp[-\kappa_{1,2}|z| + i(\vec{k}_{1,2}\vec{r} - \omega t)], \tag{3}$$

where $k = \omega/c$ and κ_1 and κ_2 are the skin depth in ordinary magnet and vacuum

$$\kappa_1 = \sqrt{k_1^2 - \epsilon_1\mu_1 k^2}, \kappa_2 = \sqrt{k_2^2 - \epsilon_2\mu_2 k^2}, \tag{4}$$

and $k_{1,2}$ are the wavenumbers of TE-modes, directed by the boundaries 'mu-megative/magnet' and 'mu-megative/vaccuum', accordingly:

$$k_{1,2} = (\omega/c)\sqrt{\mu(\omega)\mu_{1,2}/(\mu(\omega) + \mu_{1,2})}, \tag{5}$$

here indexes 1,2 refer to the regions including magnet $X < 0$, ($\epsilon_1 = 1, \mu_1 = 2.5$) and vacuum $X > 0$ ($\epsilon_2 = \mu_2 = 1$), accordingly. Vectors $\vec{r}$ lie in a plane $Z = 0$. For mu-negative metamaterial we can assume that its dielectric permittivity equal 1, and negative magnetic permeability has a form [5]:

$$\mu(\omega) = 1 - a\omega^2/(\omega^2 - \omega_0^2), \tag{6}$$

$a = 0.56, \omega_0/2\pi = 4GHz$.

It's easy from the well-known condition of equality of wavevector tangential components:

$$k_1 \sin\theta_i = k_2 \sin\theta_r \tag{7}$$

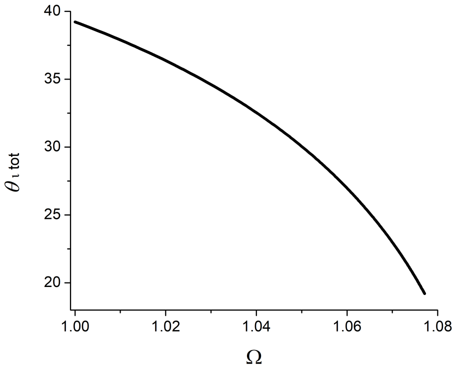

Figure 3. Values of the total internal reflection angle versus the normalized frequency for surface TE-wave

and $sin\theta_r = 1$ to obtain value for angle of total internal reflection θ_{itot}:

$$\theta_{itot} = \arcsin\sqrt{1 + (\mu_1 - 1)/(1 + \mu(\omega))}/\sqrt{\mu_1} \tag{8}$$

Results of calculation presented the Fig. 2,3 were obtained for normalized wavenumber $\beta = ck_1/\omega_0$ and normalized frequency $\Omega = \omega/\omega_0$. In Fig. 2 it presents the dispersion of surface electromagnetic TE-waves in the quite narrow frequency, in which magnetic permeability of metamaterial is less 0.

$$\frac{\kappa_1}{\mu_1} + \frac{\kappa(\omega)}{\mu(\omega)} = 0, \tag{9}$$

here $\kappa(\omega) = \sqrt{k_1^2 - \mu(\omega)k^2}$ is a penetration depth of electromagnetic surface wave energy into mu-negative metamaterial.

As can see, this wave is slow (its phase velocity is less the speed of light in vacuum) and forward (the directions of phase and group velocities coincide) [11].

In Fig. 3 presents dependence value of critical angle θ_{itot} vs normalized frequency Ω. At higher frequencies to penetrate into the area covered by the vacuum can only waves with wavevector inclined to the normal at the angles of incidence $\theta_i < 20^o$.

Certain part of energy of surface electromagnetic waves cannot escape from the mu-negative medium, because the angle of incidence is bigger than the critical angle of total internal reflection. By choosing the ratio of parameters of the mu-negative metamaterial and the magnetic material, it is possible to reduce the critical angle, which will give a higher percentage of total reflection from the vacuum boundary.

This phenomenon can be used both in waveguides and resonators. Very likely to use the effect of frustrated total internal reflection in research and diagnostics. We hope that obtained results will expand the capabilities of the element base of modern devices. The area of possible applications are: transmission and control of signals, charged particles movement control, photovoltaic and much more. More detailed study of this phenomenon will be published in short time.

We would like to acknowledge financial support by the Ministry of Education and Science of Ukraine, under the Project 2-13-21.

ORCID

Viktor Galaydych, https://orcid.org/0000-0002-2255-9716; **Mykola Azarenkov**, https://orcid.org/0000-0002-4019-4933

REFERENCES

[1] B. Cappello, and L. Matekovits, in: *2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting*, 2020, pp. 813–814, https://doi.org/10.1109/IEEECONF35879.2020.9329662

[2] I.V. Shadrivov, M. Lapine, and Y.S. Kivshar, editors *Nonlinear, tunable and active metamaterials*, (Springer, 2015). https://link.springer.com/book/10.1007/978-3-319-08386-5

[3] J.A. Girón-Sedas, O.N. Oliveira Jr., and J.R. Mejía-Salazar, Superlattices and Microstructures, **117**, 423 (2018). https://doi.org/10.1016/j.spmi.2018.03.062

[4] A.V. Zayats, I.I. Smolyaninov, and A.A. Maradudin, Physics Reports. **408**(3), 131 (2005). `https://doi.org/10.1016/j.physrep.2004.11.001`

[5] R. Ruppin, Physics Letters A 277, 61, (2000). `https://doi.org/10.1016/S0375-9601(00)00694-0`

[6] V.K. Galaydych, N.A. Azarenkov, V.P. Olefir, and A.E. Sporov, Problems of Atomic Science and Technology, 1, 96 (2017). `https://vant.kipt.kharkov.ua/ARTICLE/VANT_2017_1/article_2017_1_96.pdf`

[7] S. Lee, D.-H. Kim, H. Kim, C. Song, S. Kong, J. Park, et al., IEEE Transactions on Electromagnetic Compatibility, **60**, 4 1001 (2018). `https://doi.org/10.1109/TEMC.2017.2751595`

[8] B.R. Lavoie, P.M. Leung, and B.C. Sanders, Photonics and Nanostructures: Fundamentals and Applications, **10**(4), 602–614 (2012). `https://doi.org/10.1016/j.photonics.2012.05.010`

[9] J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart, IEEE Trans. MTT-47, **2075**, (1999). `https://doi.org/10.1109/22.798002`

[10] A.A. Maradudin, and T.A. Leskova, Physica B: Condensed Matter, **405**(14), 2972 (2010). `https://doi.org/10.1016/j.physb.2010.01.016`

[11] V. Galaydych, and M. Azarenkov, Applied Physics B, **128**, 132 (2022). `https://doi.org/10.1007/s00340-022-07854-3`

[12] V. Galaydych, and M. Azarenkov, Applied Physics A, **129**, 466 (2023). `https://doi.org/10.1007/s00339-023-06751-6`

ПОВНЕ ВНУТРІШНЄ ВІДБИТТЯ ПОВЕРХНЕВИХ ЕЛЕКТРОМАГНІТНИХ ТЕ-ХВИЛЬ

Віктор Галайдич[a], **Микола Азаренков**[a,b]
[a] *Харківський національний університет ім. В.Н. Каразіна, майдан Свободи, 4, 61022, Харків, Україна*
[b] *Національний науковий центр «Харківський фізико-технічний інститут», 61108, Харків, Україна*

Досліджено заломлення поверхневих електромагнітних хвиль (ПЕХ) на неоднорідній метаповерхні. Структура, що розглядається, містить три області: мю-негативного метаматеріалу, звичайного магнетика та вакууму. Межі між середовищами, що розглядаються, є пласкими. Було використано феноменологічний підхід, також вважалось, що всі середовища є ізотропними та в них немає втрат енергії хвиль. У цьому повідомленні показано можливість ефекту повного внутрішнього відбиття для поверхневих електромагнітних хвиль ТЕ-поляризації, що можуть поширюватись вздовж такої неоднорідної метаповерхні. Значення кута повного внутрішнього відбиття зменшується для більш високочастотних хвиль з інтервалу, що розглядається. Представлений результат може допомогти в проектуванні як дослідницьких, так і промислових складних систем.

Ключові слова: *мю-негативний метаматеріал; метаповерхня; електромагнітна поверхнева хвиля; повне внутрішнє відбиття*