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Total Reflection Investigation with Negative and Near Zero Magnetic Permeability along the Visible Light Range and All Negative Values of Magnetic Permeability along the Blue Light Range with Total Reflection

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Abstract

In this study, total reflection through a slab of vacuum and mercury nano-particle is achieved with negative and near zero magnetic permeability. It is shown that this new design of metamaterial act as an excellent reflector which could be used in many applications. This paper also shows that this optical mirror has negative values for magnetic permeability in the blue range of the visible light and total reflection in this range is achieved.

Keywords: reflection; negative refractive index; magnetic permeability; optical mirror.

1. Introduction

Almost all electromagnetic phenomena and devices result from interactions between waves and materials. In this sense, the realization of an electromagnetic functionality is meant to manipulate the waves in a desired manner by elaborating structures and geometries with available materials. One of the most fundamental assumptions in optics is that of refractive index, which gives the factor by which the phase velocity of light is decreased in a material compared to vacuum conditions. Negative index materials (NIMs) have a negative refractive index so that electromagnetic waves in such media propagate in a direction opposite to the flow of energy, which is unusual. There are no materials occurring NIMs. However, artificially designed materials called (metamaterials) can act as NIMs which was proposed by the Russian scientist Victor Veselago in 1968 [1].

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Metamaterials can be single negative metamaterials with either negative permittivity or permeability, or double negative metamaterials with negative permittivity and permeability. However, due to the negative refraction index, the direction of phase and group velocity is opposite. Potential applications of metamaterials are diverse and include optical filters, medical devices, remote aerospace applications, sensor detection and infrastructure monitoring, smart solar power management, crowd control, radomes, high frequency battlefield communication and lenses for high gain antennas, improving ultrasonic sensors, and even shielding structures from earthquakes [2,3,4,5]. Metamaterials offer the potential to create superlenses. Such a lens could allow imaging below the diffraction limit that is the minimum resolution that can be achieved by conventional glass lenses. Metamaterial research is interdisciplinary and involves such fields as electrical engineering, electromagnetics, classical optics, solid state physics, microwave and antenna engineering, optoelectronics, material sciences, nanoscience and semiconductor engineering [6].

2. Theory

To understand MMs, it is necessary to understand material response to EM waves in general. EM response in homogeneous materials is predominantly governed by two parameters. The first one is electric permitivity $\varepsilon(\omega)$ which describes the response of a material to the electric component of light and the second parameter is the magnetic permeability $\mu(\omega)$ at a frequency ω. Both parameters are typically frequency-dependent complex quantities, so there are four numbers in total that describe the response of an isotropic material to EM radiation at a given frequency,

$$\varepsilon(\omega) = \varepsilon_1(\omega) + i\varepsilon_2(\omega)$$

$$\mu(\omega) = \mu_1(\omega) + i\mu_2(\omega) \qquad (1)$$

A commonly used EM parameter is the index of refraction, which defined as $n(\omega)^2 = \varepsilon(\omega)\mu(\omega)$. The index of refraction provides a measure speed of an EM wave as it propagates within a material. In addition, the refractive index also provides a measure of deflection of a beam of light as it crosses the interface between two medias having different values of refractive indices. This was provided by Willebrord Snell in 1921[7,8] who showed that,

$$n_1 sin\theta_1 = n_2 sin\theta_2 \qquad (2)$$

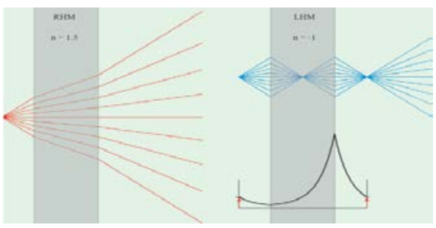

Figure 1

In figure1 a normal slab of flat glass illuminated by a point source (red lines). The rays diverge and refracted at the interface according to Snell's law (2). On the right side, a flat slab of NI material is shown with rays from a point source (blue rays) incident upon it. In this case the rays refract at the interface, also governed with Snell's law but with an index of n = -1. The black line shows the evanescent component of the blue point source which is focused by this unique lens. Nature has hidden a great secret from us, this secret was discovered by the Russian physicist Victor Veselago [9]. Veselago realized that if a material had negative values for both electric and magnetic response functions, then its index of refraction would be negative.

3 Modeling and Calculations

3.1 Reflectance, transmittance and materials properties at the visible range

The design consists of a slab of vacuum with mercury nanoparticle (80nm) at the end of the slab in figure2, the component is directed along z-axis, I applied an electric field along x-axis and magnetic field along y-axis with open boundaries on z-axis. The range of wavelength is between 350-700nm.

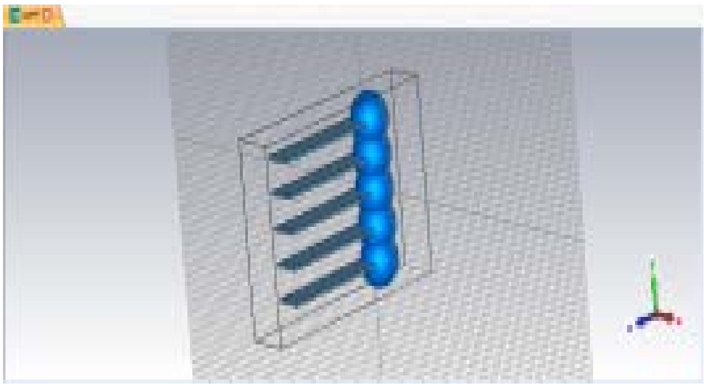

Figure 2: 3D full field electromagnetic simulation geometry with CST.

I plot reflectance graphs versus wavelength range in figure3 which shows an excellent reflection with an average reflectance 100% at the range 490-420THz, and the other range at 420-450THz, then it continue with total reflection at 450-700THz, while it is totally the opposite in the transmittance graphs in figure4.

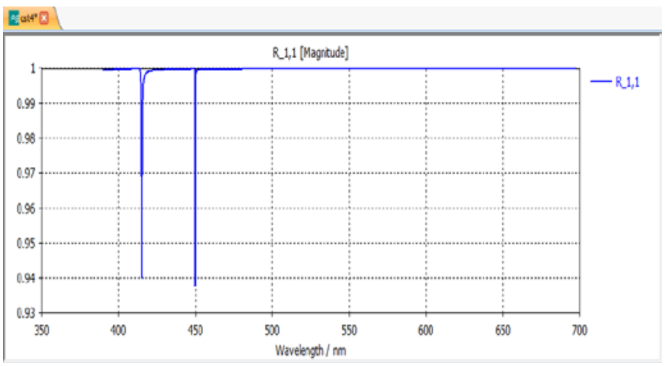

Figure 3: Magnitude of the reflected waves

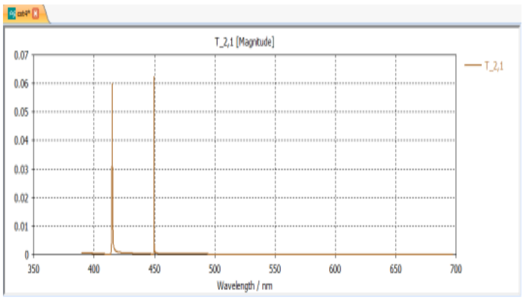

Figure4: Magnitude of the transmitted waves

Figure5 and figure6 show the magnitude of the reflected and transmitted waves in dB verses wavelength.

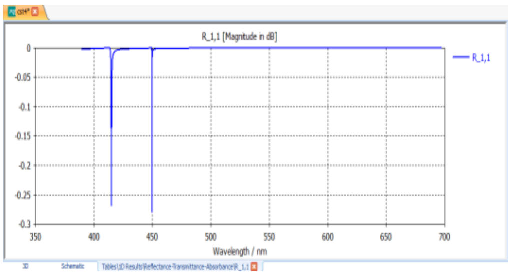

Figure 5: Magnitude of the reflected light in dB

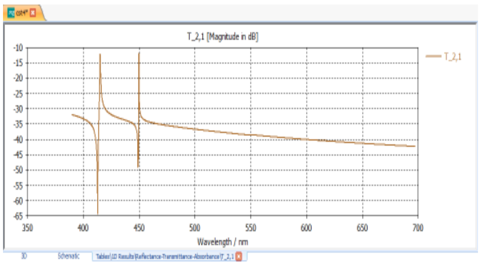

Figure 6: Magnitude of the transmitted light in dB

In the figure7 below I present the materials properties after the simulation, it shows that this combination of vacuum and mercury give a negative and near zero magnetic permeability which is difficult to be achieved in nature. In this figure I plot the magnetic permeability verses frequency.

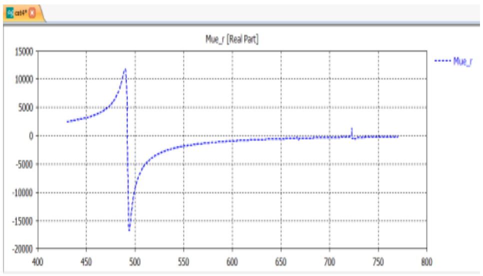

Figure 7: Real part of the magnetic permeability

According to the figure7 we can see that at frequency range 430-491.96THz, it exhibits high positive values of the permeability, then it goes down to the negative range of the permeability with a value of (-16732) at 494.26THz. It continues in the negative values and near zero at frequency range 496.96-770.93THz.

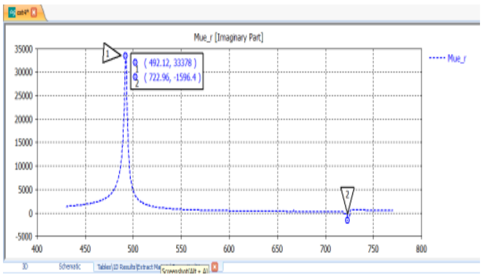

Figure 8: Imaginary part of the magnetic permeability

Figure8 shows the imaginary part of the permeability, it goes up positively and reach a high value (33378) at 492.12THz then it decreases taking near zero until a small curve with a negative value (-1596.4) at 722.96THz.

Figure9 present the graphs of electric permittivity, the electric permittivity took negative and near zero values (-200-0) at the frequency range 430.85-500THz, then it fluctuate with positive values at 500-770THz with a notice of exhibiting high positive value about 1070 at frequency 720THz.

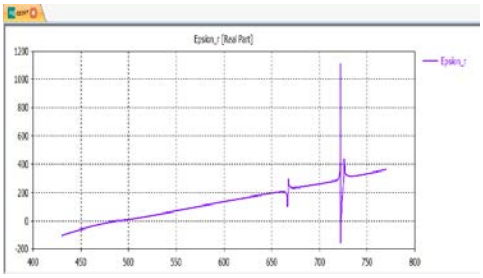

Figure 9 Real part of the permittivity

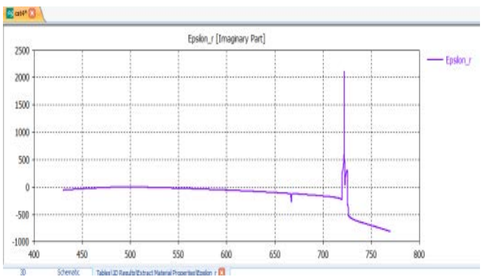

Figure 10 Imaginary part of the electric permittivity

From figure10 the permittivity takes values from zero and decrease negatively along the frequency range 430.85-720THz then it fluctuates taking high positive values then it goes back again negatively.

The last parameter is refractive index. In figure11, I plot the real part of the refractive index which takes negative values (-300-0) at frequency range 430.85-523.68THz, this graph has four shift points as it's seen in the figure below.

The effect that n varies with frequency is known as dispersion, and it is what causes a prism to divide white light into constituent spectral colors, explains rainbows. In regions of the spectrum where the material dose not absorb, the real part of the refractive index tends to increase with frequency. Near absorption peaks, the curve of the refractive index is a complex form and can decrease with frequency.

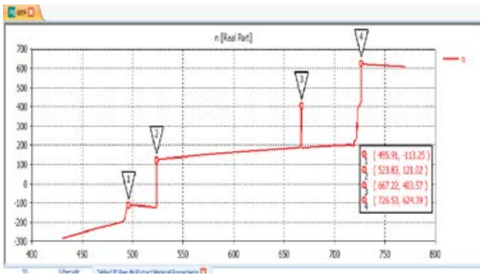

Figure 11: Refractive Index

3.2 Reflectance, transmittance and materials properties at the blue visible range

In this section I will present the EM properties of the vacuum-mercury metamaterial in the blue range of the visible light. This study gives near perfect reflection with negative values of the magnetic permeability along the blue range. Figure12 shows the real part of the permeability and permittivity verses the frequency.

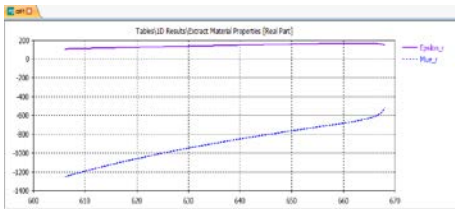

Figure 12: Real part of μ_r and ε_r

Figure13 shows the three parameters n, μ_r and ε_r verses the frequency.

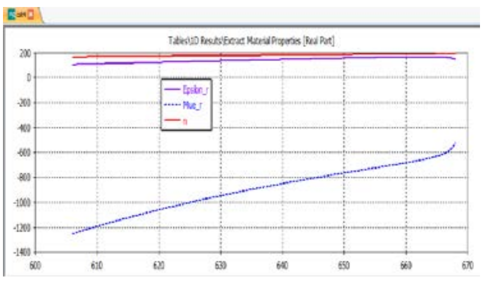

Figure 13: Refractive index, permeability and permittivity

Reflectance and transmittance are presented in the figure14 below. It shows total reflection in the blues light range of the visible light.

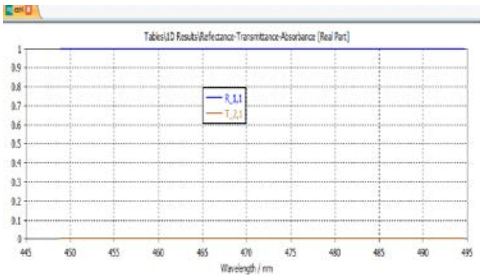

Figure 14: Reflectance and transmittance

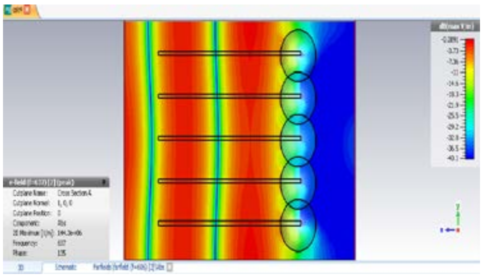

Figure 15: The electric field in dB

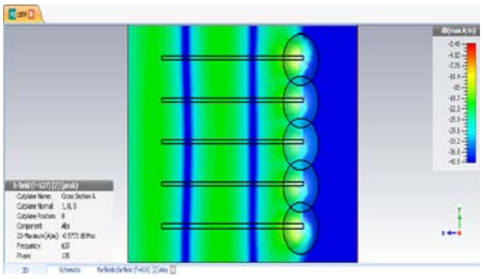

Figure 16: The magnetic field in dB

In the later figures I plot the power flow at different frequencies (606,637,668THz)

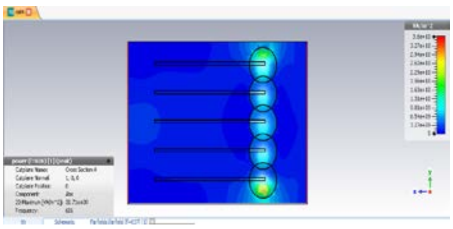

Figure 17: Power flow at 606THz

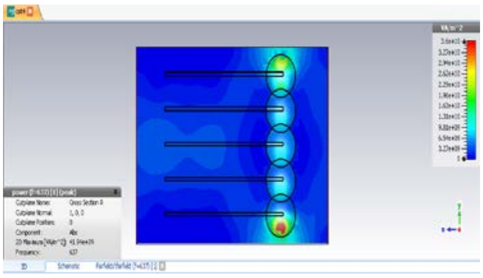

Figure 18: Power flow at 637THz

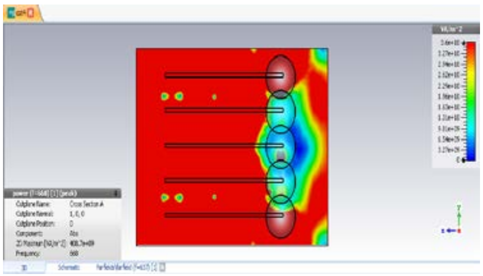

Figure 19: Power flow at 668THz

4. Conclusion

Analysis and simulation of the proposed structure was carried out with help of a simulation software. The proposed work was modeled and simulated using CST microwave suite studio, an electromagnetic simulation software tool for high frequency ranges which based on finite element modeling method. In this paper, the reflection and transmission properties of the vacuum-mercury structure is studied at both optical ranges (visible range and blue range). It has been found that this structure gives an excellent reflection in the visible range, it also gives negative and near zero values of the permeability which lead to negative refraction index, while this structure in the blue range gives total negative permeability with total reflection along this range. At the end, vacuum-mercury structure work as a reflector which could be used in imaging or in laser technology as a mirrors.

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