Investigation of negative refraction in composite ferrite-semiconductor prism for millimeter waveband

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Abstract

The paper is devoted to experimental study of left-handed properties of prism-shaped metamaterial consists of ferrite and semiconductor bricks oriented in the staggered order in millimeter waveband. The negative refraction was revealed. The appearance of double negative frequency zone has been demonstrated experimentally and theoretically. Satisfactory agreement between experiment and numerical results is shown. The dependence of double negative zone position on the external magnetic field, caused by ferromagnetic resonance in ferrite elements has been detected and analyzed.

1. Introduction

There are several methods to verify the left-handed metamaterial (LHM) properties. One of them is realizing the prism-like experiment. The second one is measuring the lateral shift of a Gaussian beam happening on slab of LHM metamaterial. In this article, authors present another one method to verify left-handed properties of metamaterial, based on T- junction waveguide measurement [1].

The phenomenon of negative refraction in materials with simultaneously negative ε and μ have been predicted by Veselago [2] and was experimentally demonstrated in microwave scattering experiments [3]. Experimental demonstration of negative refraction for millimeter waveband and for metamaterials formed by natural elements has been realized (for inst. [4, 5]). In particular, in [4] the left-handed properties of 1D prism provided by alternating layers of ferrite and semiconductor have been studied. However, no experiments were performed with a 2D prism provided by ferrite and semiconductor bricks, alternating in a staggered order. Due to mixing of ferrite and semiconductor elements oriented in a staggered order, the more high degree of metamaterial homogenization than in the case of 1D prism can be achieved. Thus with the aim of negative refraction demonstration the experimental study of the LHM properties of 2D prism is performed.

2. Experimental details

The two-dimensional (2D) structure was used for experiment (Fig. 1).

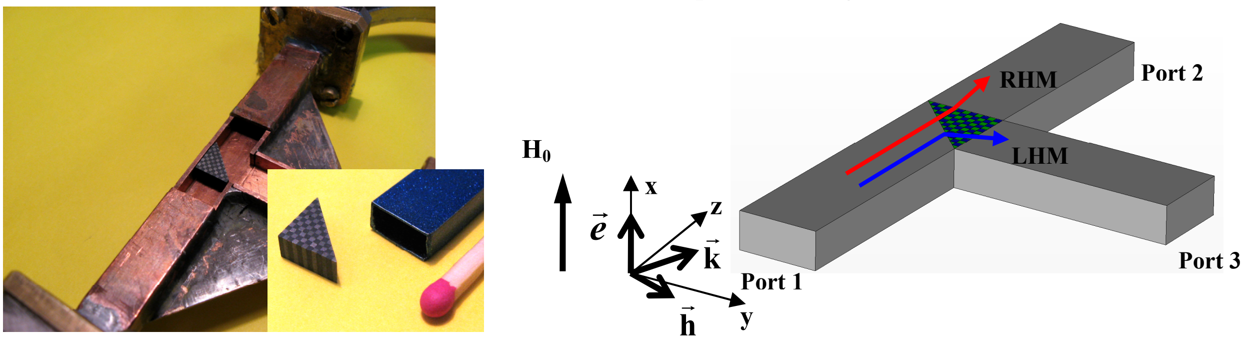

Fig. 1 – The T-junction waveguide with metamaterial prism: photo (left); scheme (right)

The composite prism type 45-90-45 degree, used in the experiment (Fig. 1) consists of ferrite (brand 1SCH4) and semiconductor (n-InSb) bricks, alternating in a staggered order. The ferrite brick (cross-section $0.5\times0.5mm^2$) has the complex permittivity $\varepsilon_f = 11.1$, and the saturation magnetization is $4\pi Ms = 4800G$, damping coefficient is $\alpha = 0.024$. The InSb semiconductor brick (cross-section $0.5\times0.5mm^2$) has the following parameters: lattice permittivity is $\varepsilon_0 = 17.8$. The triangle prism (with cathetuses of 7.2 *mm*) is formed by 12 elements on each side. The thickness of the prism is 3.4 *mm*. The composite structure was embedded into hollow T-junction waveguide of H-type with cross-section $7.2\times3.4mm^2$. Two T-junction waveguide ports: port 2 (S21) and port 3 (S31) were connected to attenuators to calibrate transmission coefficients through the metamaterial at zero magnetic field. An electromagnetic wave propagates along the *z* axis with an electric field along the *x* axis and magnetic field along the *y* axis. The external static magnetic field $\mathbf{H_0}$ was changed in the range of 0–10 kOe and applied normally to alternating magnetic field (Fig.1). The transmission coefficient was measured in the 22-40 GHz frequency range with use of Agilent Vector Analyzer PNA 5230A.

3. Results and analysis

It is known that in the frequency range, where effective negative permittivity region of composite structure $\varepsilon'_{eff} < 0$ and negative permeability region of composite structure $\mu'_{eff} < 0$ overlap, the transmission Double Negative (DNG) peak can be registered [6]. So we investigated the transmission properties of the prism just in this frequency range. The transmission through T-junction was calibrated to zero level at H = 0 Oe. Experimental results on measuring the transmission spectrum of the composite prism at magnetic field 7240 Oe are given in Fig. 2(a).

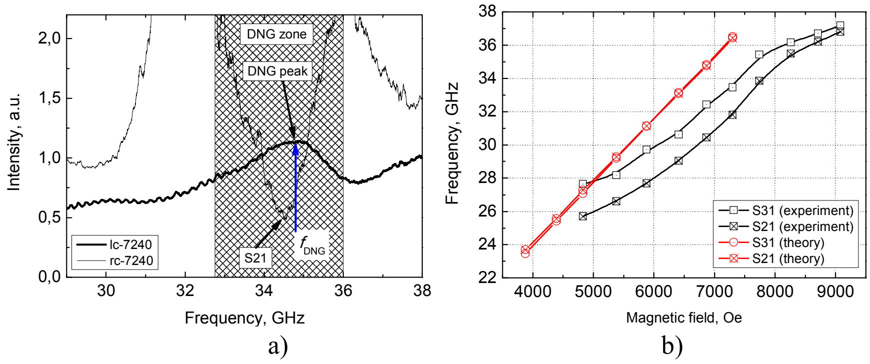

Fig. 2: Experimental results for transmission spectrum of the composite prism on magnetic field 7240 Oe(a); dependence of the transmission peak intensity on the magnetic field (b)

It is seen that in the DNG zone of the prism the transparency peak (DNG peak) for port 3 (S31) and the dip for port 2 (S21) near the frequency of $f_{DNG} = 34.6$ GHz (Fig. 2a) appear. This transparency peak should be associated with the negative refraction in a prism. To confirm this we should take into account that at the frequency of maximum transparency (f_{DNG}) a backward wave should be occurred in the metamaterial. To analyze this we calculated the spatial distribution of electromagnetic field by FDTD method in the composite prism at a frequency of $f_{DNG} = 36.2$ GHz at various magnetic field magnitudes. The field pattern at H=7240 Oe is presented in Fig. 3.

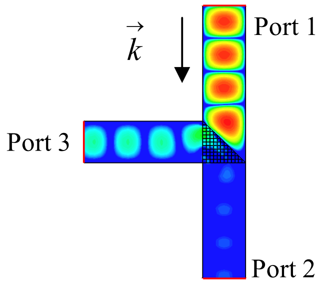

Fig. 3: The distribution of E-component of the EHF-field for T-junction (H=7240 Oe, $f = 36.2$ GHz)

One can see that the electromagnetic wave is bended to the port 3 (S31), at H=7240 Oe, $f = 36.2$ GHz (Fig. 3). At the same time the electromagnetic wave is strongly damped in the direction of the port 2 (S21). This scenario testifies that the prism demonstrates left-handed properties, namely it the negative refraction takes place.

The dependence of the DNG zone as function of external magnetic field has been analyzed theoretically and experimentally Fig. 2(b). The satisfactory agreement between experimental data and theoretical ones is occurred. The difference between the slope of the theoretical and experimental curves can be attributed to mismatch of material parameters used in the calculation and experimental.

4. Conclusion

Thus,

The experimental study of left-handed properties of 2D prism consists of ferrite and semiconductor bricks oriented in staggered order in the millimeter waveband have been performed. The negative refraction has been revealed.

The appearance of double negative frequency zone has been demonstrated experimentally and theoretically.

A satisfactory agreement between experiment and numerical results is shown. The dependence of DNG zone position on the external magnetic field, caused by FMR in ferrite elements has been detected and analyzed.

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