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MICROWAVE ELECTRODYNAMICS

Left-Handed Properties of Metal-Ferrite Composites Placed into Waveguide in Millimetric Wave Range

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ABSTRACT: Propagation of the electromagnetic wave of millimeter wavelength through the composite media formed by alternated ferrodielectric and metal elements, embedded into waveguide, has been investigated. It was shown experimentally that the composite media demonstrate left-handed properties in certain frequency region (Double Negative Region), depended on the static magnetic field. The magnification of transmittance of structures under study has been detected and analyzed.

INTRODUCTION

Left-handed medium (LHM) ($\varepsilon' < 0$ and $\mu' < 0$) is one of most striking examples of artificial medium (metamaterials), which property are unattainable for natural materials [1]. Design of LHM can lead to development of superlens with superresolution, invisible coverings for microwave and optical ranges (cloaking system), etc. [2]. The problem of LHM making is established, so there are many works, experimental and theoretical, concentrated on it, but still it remains many obstacles and search proceeds.

The given work devotes to experimental study of peculiarities of some types of LHM, with different types of primary elements, forming the medium. Among a plenty of possible types of primary elements we have chosen the alternating layers. Such types of primary element for LHM have quite good perspectives on the reason of simple LHM-properties control. Namely, in our work we have investigated the LHM, composed by ferrite layers as origin of the negative

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permeability and metal deposited wires (Wire Medium (WM)) or Cu- , Ni- plate structure as an origin of the negative permittivity. We have found the frequency range, where the LHM transmission coefficient is quite high. It was shown that this frequency band, called as Double Negative Region (DNG-region) [4], is assigned to appearance of LHM properties and lies near the ferromagnetic resonance (FMR)-peak for the ferrite.

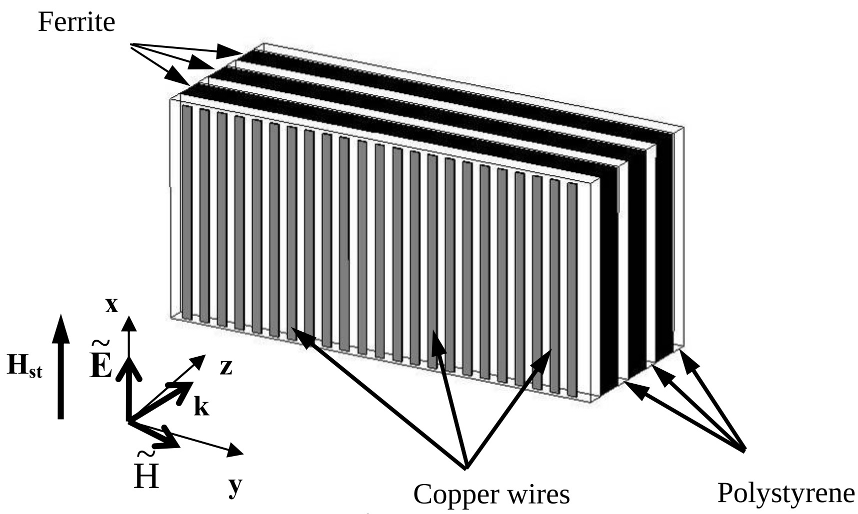
EXPERIMENT AND ANALYSIS

Ferrite/wire-medium structure

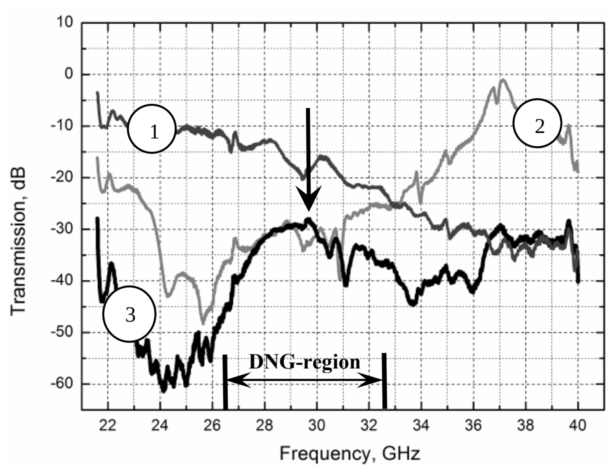
In order to define the LHM conditions for the medium, where the negative permittivity is formed by the structure with spatially separated constitutive parameters, the wire medium was used. Thus the first investigated structure consisted of three flat parallel ferrite plates alternating with four polystyrene plates with deposited flat copper wires on it (Fig. 1) has been analyzed. Such LHM structure has been placed into the one-mode waveguide with cross-section 7.2x3.4 mm^2 and investigated in the frequency range of 22.0-40.0 GHz. The thickness of ferrite layer is $d^f = 0.5$ mm and its permittivity is $\varepsilon'_f = 11.1$. Wire medium was made by copper stripes with thickness $d_z^w = 0.025$ mm, width $d_y^w = 0.15$ mm and length $d_x^w = 7$ mm and $h = 0.3$ mm periodicity along **y** axis, deposited on the polystyrene substrate with thickness $d_z^p = 0.3$ mm and permittivity $\varepsilon'_p = 2.56$. The static magnetic field (H_{st}=0÷7 kOe) vector was directed perpendicularly to alternating magnetic field vector $\tilde{\mathrm{H}}$ (see Fig. 1). Note that the optical width value of each element of LHM is approximately in 5 times less than the wavelength. So we can use terms as “the effective/averaged permittivity/permeability of the medium” to describe the given structure effective constitutive parameters.

Experimental results are presented in Fig. 1(b). One can see there spectra: for WM (1), for ferrite-layer medium (2) and for ferrite/wire-medium structure (3). Experimental results show the presence of the transmission peak in the band of 26.5- 32.0 GHz having maximum height of -30 dB (arrow in Fig. 1(b)). The height of this transmission peak is almost 20 dB higher then additive transmission coefficients formed by formal summing of coefficients for wire-medium (1) and ferrite layers (2) for the given frequency range.

This peak is an analog of the peak corresponded to Double Negative Region and studied for instant in [4]. It caused by that reason that for 26.5-32.5 GHz both of effective constitutive parameters are negative, that is equivalent to appearance of left handed medium (LHM). Also the tuning of DNG-region position by magnetic field was observed. This is caused by shifting of FMR band position with change of the external magnetic field $\mathbf{H}_{st}$ strength. Note that ferrite as a known ferrodielectric demonstrates a negative permeability for some definite range of magnetic field. This range shows itself in the vicinity of FMR-peak and in its high-frequency part [5]. At the same time the effective permittivity remains negative, because the plasma frequency [3] for given WM is about 300 GHz.



a)



b)

FIGURE 1. (a) Ferrite/wiremedium structure. (b) Experimental transmission coefficient for ferrite/wire-medium structure and its components. H_{st}=6.84 kOe. (1)-WM: consists of 4 wire-media layers, (2) - ferrite- layer medium: consists of 4 ferrite layers, (3) – ferrite/wire medium structure: consists of alternated 4 wire-media layers and 3 ferrite layers.

Ferrite/thin-metal-layer structure

In order to define the LHM conditions for the medium, where the negative permittivity is formed by material with spatially homogeneous constitutive parameters, the thin metal plane instead of wires was used. This experimental realization of such LHM structure was made by combining the same ferrite layers as in above mentioned case, but with thin copper (or nickel) layers deposited on mica substrate between. Each layer is partially transparent for used frequency range. This composite structure was placed into the same waveguide and investigated in frequency range of 21.0-40.0 GHz under static magnetic field H=0÷7 kOe as it showed in Fig. 2. The copper layer with thickness $d_z^{Cu} = 100 \div 150$ nm and nickel layer $d_z^{Ni} = 90 \div 100$ nm was deposited on mica layer with thickness $d_z^m = 0.03$ mm and permittivity about of $\varepsilon'_m = 10$.

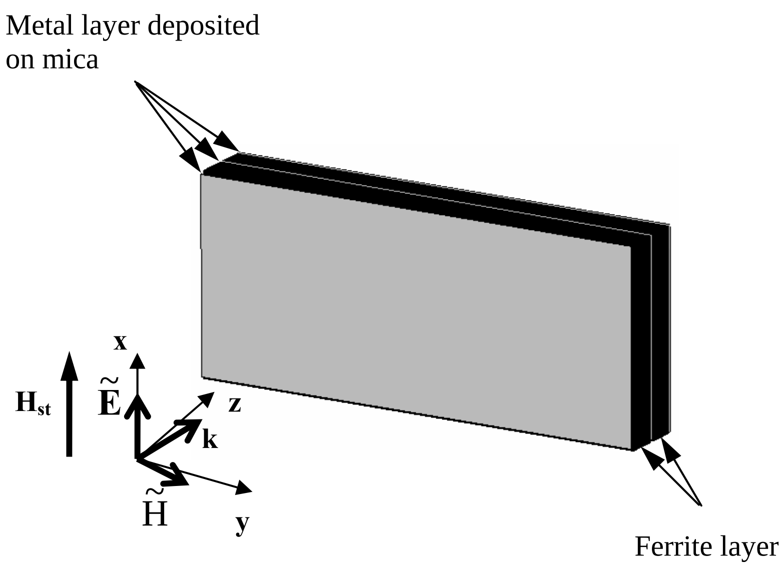
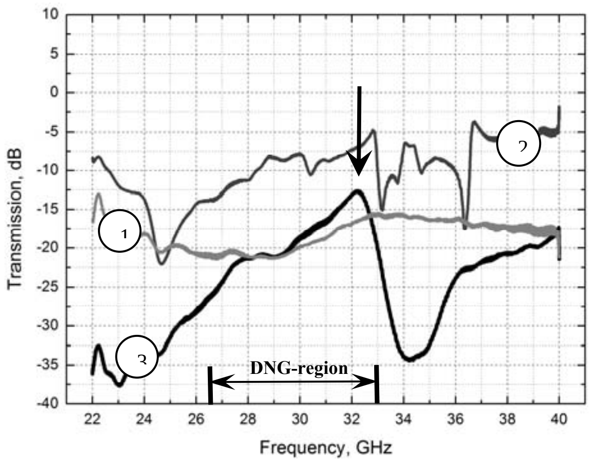
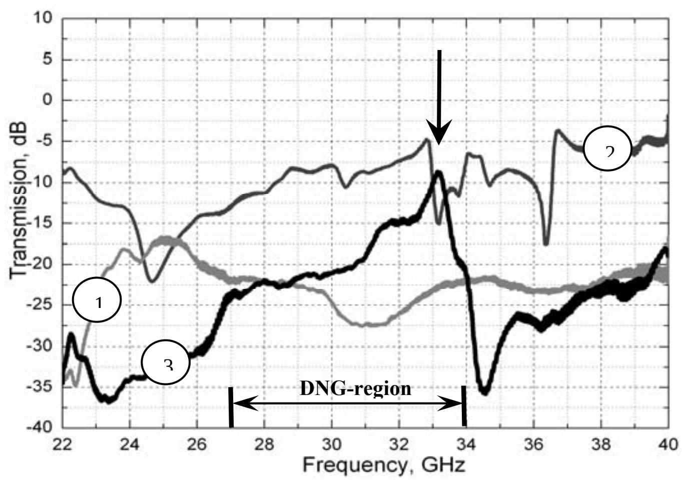


FIGURE 2. Ferrite/thin-metal-layer structure.

The results are presented in Figs. 3(a) and 3(b). As well as in Fig. 1(b) one can see here the spectrum for thin-metal-layer structure (1), the spectrum for ferrite-layer medium (2) and the spectrum for ferrite/thin-metal layer structure (3). One can see the presence of transmission peaks (DNG-regions) as well as for ferrite/wire-medium case. In the case of nickel layers it appears in the frequency band 26.5-33.0 GHz.



a)



b)

FIGURE 3. Experimental transmission coefficient for ferrite/thin-metal-layer structure. H_{st}=7.0 kOe. (a) ***ferrite/nickel thin-metal-layer structure:*** (1) nickel thin metal layer: consists of 3 nickel deposited layer, (2) ferrite-layer medium: consists of 2 ferrite layers, (3) ferrite/nickel thin-metal layer structure: consists of alternated 3 nickel deposited layer and 2 ferrite layers. (b) ***ferrite/copper thin-metal-layer structure:*** (1) copper thin metal layer consists of 3 copper deposited layer, (2) ferrite medium: consists of 2 ferrite layers, (3) ferrite/copper thin-metal layer: consists of alternated 3 nickel deposited layer and 2 ferrite layers.

For Fig. 3(a) the maximum transmission coefficient reaches the magnitude - 12 dB (arrow in Fig. 3(a)) that is 12 dB bigger, than the additive transmission coefficient obtained by formal summing of coefficients for thin-metal-layer (1) and ferrite-medium layer (2). Easy to see that the DNG-region is more explicit for this case, than for the case of ferrite/wire-media structure. This seems to be naturally because in the latest case the media under study is more homogeneous. Moreover, for the case of copper layers (Fig. 3(b)) the left-handed behavior of the composite structure is even more evidently. Namely, the DNG-region, which appears in the band 27.0-34.0 GHz with maximum height -8 dB (arrow in Fig 3(b)) is almost 30 dB bigger than additive transmission coefficient.

As will be see from Fig. 3(b) the maximum of transmission coefficient for composite structure is even higher than the transmission coefficient for the best of composing materials for frequency band 33.0-33.5 GHz. Probably this phenomenon is caused by the optimal matching between the structure elements.

The magnetic tuning of transmission peak position was observed in the same way as in the ferrite/wire-medium composite and can be explained in same way as in previous case.

CONCLUSIONS

Thus, have been investigated experimentally spectral properties of three composite magneto-controlled structures. It is demonstrated experimentally that the investigated structure possesses magnetically controlled LHM properties in the whole frequency band under research. It is shown that the left-handed transmission peak can be obtained by using not only wire system but also with system of thin-metal films. The conductivity of the metal affects on the transmission peak magnitude and the frequency position of DNG-region.

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