Numerical modeling of transmission of electromagnetic waves through the 3d magnetic opal-based metamaterial structures in waveguides at millimeter waves

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The 3D magnetic metamaterials based on the opal matrices of close packed SiO_2 spheres with magnetic nanoparticles infiltrating in voids between the spheres have interesting and potentially useful electromagnetic properties at GHz and THz frequencies, tunable by external bias magnetic field [1]. The ferromagnetic resonance and waveguide transmission and reflection measurements were performed on magnetic opals at millimeter (mm) waves, demonstrating the tunability of the RF signal at resonance [1]. The goal of the present work is the accurate electromagnetic modeling of the effect of magnetic field on the scattering of the electromagnetic waves (EMW) on 3D magnetic opal-based metamaterial structures in waveguide at mm waves.

The mathematical model is based on solving the 3D diffraction boundary problem for the Maxwell's equations with electrodynamic boundary conditions, complemented with the Landau-Lifshitz equation of motion of the magnetization vector with the exchange term, without any simplification of the equations and boundary conditions [2].

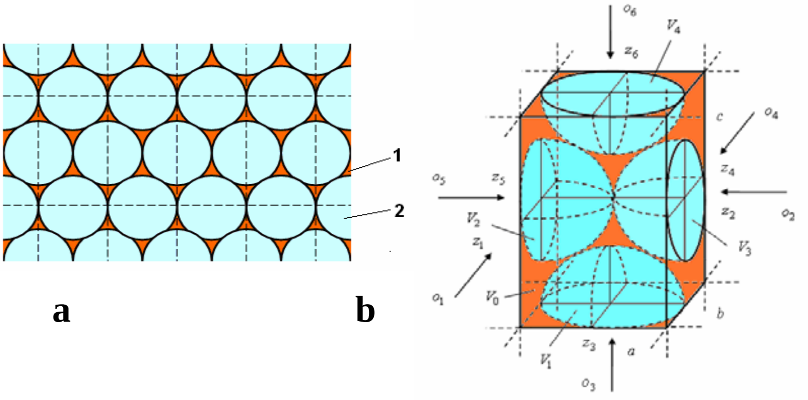

Fig.1. Division of the 3D magnetic opal into autonomous blocks: **a** – 1 – region, filled with magnetic nanoparticles; 2 – SiO_2 nanospheres; **b** – autonomous block in the form of a rectangular parallelepiped with virtual Floquet channels: V_0 is the basic region; $V=V_1\cup V_2\cup V_3\cup V_4$ are regions of dielectric nanospheres; V_0-V is the region of magnetic nanoparticles; $0_\alpha z_\alpha$ (α=1,2…,6) are local coordinate systems on input sections S_α (bounds).

The computational algorithm for the calculation of scattering matrix **R** of 3D metamaterial structures in the waveguides is developed using the decomposition approach based on autonomous blocks with Floquet channels (FAB) [2].

The domain of the 3D opal-based magnetic nanocomposite is divided into FAB (Fig.1a) in the form of a rectangular parallelepipeds, containing the opal nanospheres and magnetic nanoparticles, filling the octahedral and tetrahedral void regions (Fig.1b), with virtual Floquet channels on bounds (input sections S_α). The FAB descriptor (a multimode multichannel scattering matrix or conductivity matrix) is determined by solving the 3D diffraction boundary problem by using the Galerkin's projection method [2].

The conductivity matrix **Y** described the diffraction of EMW on 3D metamaterial structure in the rectangular waveguide is obtained as a result of the multilevel decomposition on FABs using the

FAB descriptor (conductivity matrix) [2]. Then the conductivity matrix **Y**, using the basis of the eigenwaves of Floquet channels, is transformed using the basis of the eigenwaves of the rectangular waveguide and the scattering matrix **R** is determined as $\mathbf{R} = (\mathbf{I}+\mathbf{Y})^{-1}(\mathbf{I}-\mathbf{Y})$.

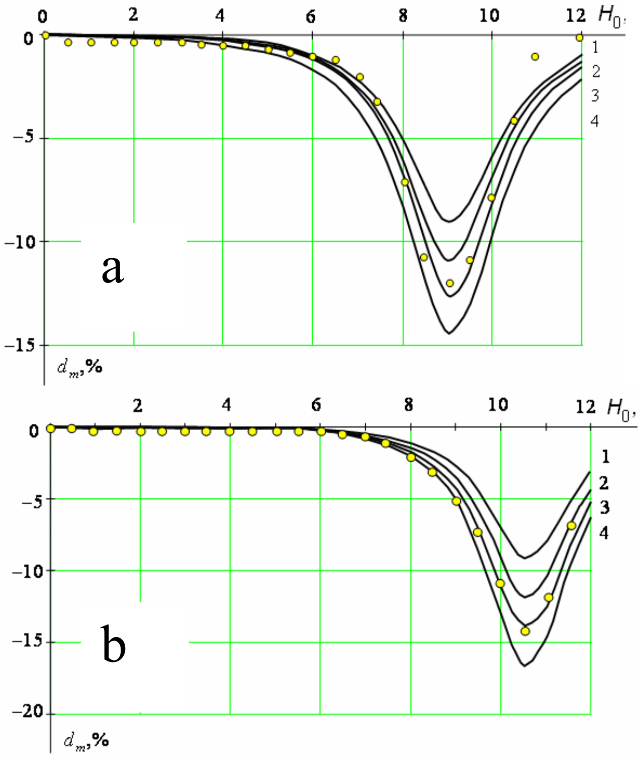

Fig.2. Calculated bias field H_0, kOe, dependence of the d_m, %, relative transmission coefficient variations of the H_{10} mode at **a** – 26 GHz, **b** – 30 GHz for a magnetic opal-based metamaterial composed of SiO_2 spheres (r = 125 nm, $\varepsilon_r = 4.6 - i3\cdot10^{-4}$, $\mu_r=1$; and the infiltrated with $Ni_{0.7}Zn_{0.3}Fe_2O_4$ ($4\pi M_s$=5kG, α=0.1, $\varepsilon_r = 9.5 - i0.3$) nanoparticles with different filling factors: 1 – 30%, 2 – 40%, 3 – 50%, 4 – 60%. Circles mark experimentally measured data from [1].

Using the scattering matrix **R**, the unknown magnitudes c_1^-, c_2^- of reflected and transmitted H_{10} mode through the 3D metamaterial structure in the rectangular waveguide are determined (assuming the magnitude of incident H_{10} mode on the input cross-section c_1^+=1). Application of the numerical algorithm to solve the diffraction problem described above, the transmitting of H_{10} mode on the magnetic metamaterial slab (thickness 1 mm) inserted into a rectangular waveguide were modeled at mm waves for the transverse orientation of bias magnetic field $\boldsymbol{H_0}$. The metamaterial structure is composed of a SiO_2 nanosphere matrix with r = 125 nm, $\varepsilon_r = 4.6 - i3\cdot10^{-4}$, $\mu_r = 1$; and the infiltrated magnetic nanoparticles are made of $Ni_{0.7}Zn_{0.3}Fe_2O_4$ having $4\pi M_s = 5$kG, $\alpha = 0.1$, $\varepsilon_r = 9.5 - i0.3$.

The transmission coefficient T_{21} for the H_{10} mode in the magnetic metamaterial-filled waveguide depends on the magnitude and direction of $\boldsymbol{H_0}$. Therefore, the T_{21} coefficients were calculated for $\boldsymbol{H_0}$ perpendicular $\boldsymbol{H_0}\perp\boldsymbol{h_{rf}}$ and parallel $\boldsymbol{H_0}//\boldsymbol{h_{rf}}$ to the plane of microwave magnetic field $\boldsymbol{h_{rf}}$. The results of calculation of the relative transmission coefficient variations $d_m=[T_{21}(H_0)- T_{21}(0)]/ T_{21}(0)$. %, depending on the transverse bias magnetic field $\boldsymbol{H_0}\perp\boldsymbol{h_{rf}}$ at 26 and 30 GHz are shown in Fig.2 for several values of the filling factor of the ferrite in the opal voids.

The agreement with the measured values is rather good if one assumes 50% filling by ferrite nanoparticles of the voids in the opal structure. According to the SEM micrographs, published in

[1], the measured values show 50-60% filling. This good agreement shows the robustness of the algorithm, despite the real ferrite in the opal structure has a particle size distribution.

The results for the relative transmission coefficient d_m at 26 GHz and 30 GHz are shown for the Ni-Zn ferrite opal-based metamaterial structure for $\boldsymbol{H_0}//\boldsymbol{h_{rf}}$ in Fig.3. With increasing frequency the position of resonance moves to higher fields, and the amplitude of the resonance increases for $\boldsymbol{H_0}\perp\boldsymbol{h_{rf}}$ (Fig.2), while it decreases for $\boldsymbol{H_0}//\boldsymbol{h_{rf}}$ (Fig.3).

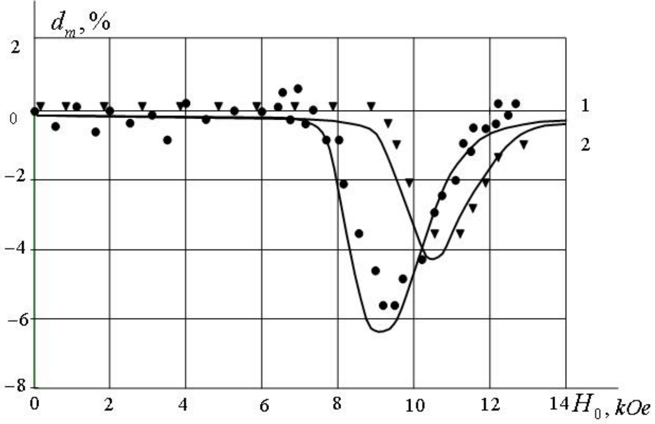

Fig.3. Bias field dependence of the relative transmission coefficient variations d_m of the H_{10} mode through the waveguide with a 3D magnetic opal-based metamaterial insert for $\boldsymbol{H_0}//\boldsymbol{h_{rf}}$, the size of the SiO_2 opal spheres is $2r$=250 nm, the filling factor for the $Ni_{0.7}Zn_{0.3}Fe_2O_4$ particles is 50%/ 1 – f=26 GHz, 2 – f=30 GHz. Markers denote experimentally measured date from [1].

Using developed numerical approach it is possible to estimate the efficiency of the interaction of EMW modes with 3D magnetic structures in waveguides, and to optimize the magnetic opal-based metamaterials for new devices, in particular, attenuators and phase shifters at microwave and mm waves.

References

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