7th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics – Metamaterials 2013
Bordeaux, France, 16-21 September 2013

Refractive index of 3D-nanocomposites with transition-metal nanoparticles

A.B. Rinkevich[1], D.V. Perov[1], M.I. Samoylovich[2], S.M. Klesheva[2], E.A.Kuznetsov[3]

[1] Institute of Metal Physics, Ural Branch of Russian Academy of Sciences
18 S. Kovalevskaya St., 620990, Ekaterinburg, Russia
[2] Central Research Technological Institute "TECHNOMASH"
4 I. Franko St., 121108, Moscow, Russia
[3] Niznij Tagil State Social Pedagogical Academy
57 Krasnogvardejskaya St., 622031, Nizhny Tagil, Russia
rin@imp.uran.ru

Abstract **– Investigation and application of extraordinary electromagnetic properties of metamaterials and nanocomposites becomes one of the most promising topics in last years. The problem of interaction between electromagnetic wave and magnetic nanoparticles is of essential interest. Resonance phenomena in 3D opal-based nanocomposites are studied here through frequency and magnetic field dependences of the transmission and reflection coefficients measured in millimeter waveband. Observation of magnetic antiresonance phenomenon is reported in a 3D-nanocomposite based on opal packages with embedded metallic magnetic particles. The antiresonance is seen at microwave frequencies of the millimeter waveband and it results in distinct maximum of the reflection or transmission coefficients.**

I. Discussion

The opal matrix packages with sphere diameter of ~ 250 nm were produced with transition metal Fe, Ni and Co nanoparticles in the inter-sphere voids. The inserted particles have polycrystalline structure and are irregular in shape, see Fig.1. The typical size of the particles falls in the interval from 5 to 60 nm. The magnetization curve measured at room temperature is shown in Fig.2. In the field interval used there is no sign of saturation and the magnetization curve looks as a straight line.

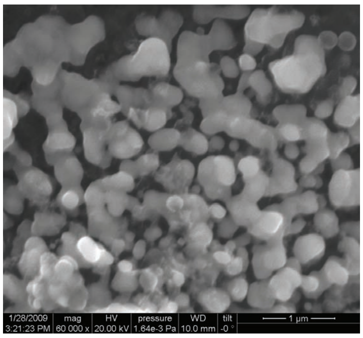

Fig. 1. Structure of 3D-nanocomposite with Co nanoparticles.

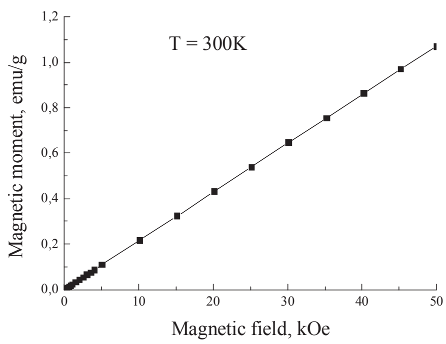

Fig. 2. Magnetization curve for 3D-nanocomposite.

Microwave measurements have been carried out in the millimeter waveband in frequency range from 26 to 38 GHz. For measurements the sample was placed inside a cross-section of the rectangular waveguide. External magnetic field ***H*** lies in the plane of the sample perpendicularly to the microwave magnetic field vector $\boldsymbol{H}_{\sim}$. The relative variation of the transmission and reflection coefficient module in magnetic field is measured. External permanent magnetic field can essentially change the reflection and transmission coefficients of the 3D-nanocomposites studied. It is usually assumed that the main reason for these variations is magnetic resonance in

Authorized licensed use limited to: Ural Federal University. Downloaded on May 17,2022 at 10:02:12 UTC from IEEE Xplore. Restrictions apply.

magnetic particles. We demonstrate here another reason of strong microwave variations besides the magnetic resonance. Let us discuss the magnetic field dependence of reflection coefficient measured at different frequencies (Fig.3).

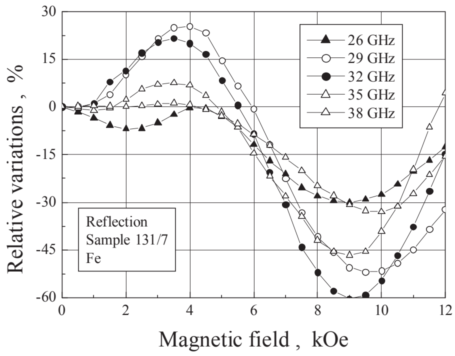

Fig. 3. Magnetic field dependences of reflection coefficient for the nanocomposite with Fe particles measured at different frequencies of millimeter waveband.

The reflection coefficient at first increases and then decreases after a maximum, reaches a minimum caused by magnetic resonance and then increases again. The maximum is seen often in the transmission coefficient also, and therefore there is a minimum of absorbed power near the maximum, that is antiresonance. This picture is typical for magnetic resonance and the minimums of reflection and transmission coefficients observe because of great imaginary part of magnetic permeability. Certainly, the resonance line for the 3D-nanocomposite is very wide as long as the metallic particles are irregular in shape and randomly oriented.

From the fields of magnetic resonance and antiresonance the spectra were reconstructed, see Fig.4a. Antiresonance is always seen in the fields less than the resonance field. The analogous results were obtained for the nanocomposite with Co particles [1]. The frequency dependences of resonance and antiresonance magnitude are shown in Fig.4b for several nanocomposites. It is clearly seen that the resonance magnitude for the nanocomposites containing the particles of two transition metals much exceeds the magnitude for the nanocomposites with the particles of one metal. The results obtained and great variations of microwave parameters create suppositions for developing of magnetic field driven microwave devices based on magnetic resonance or antiresonance.

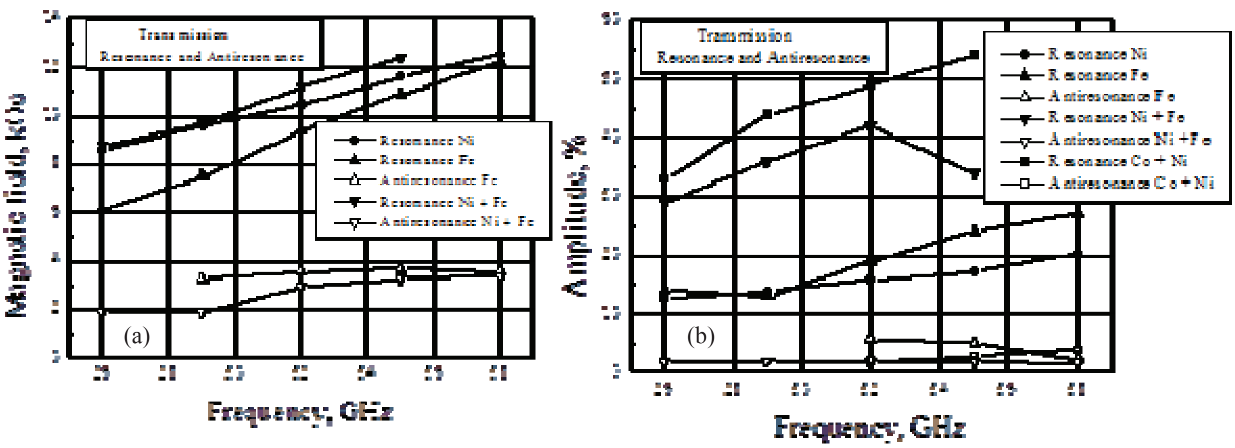

Fig. 4. Spectra of magnetic resonance and antiresonance (a) and frequency dependences of the magnitude of resonance and antiresonance for different nanocomposites (b).

Authorized licensed use limited to: Ural Federal University. Downloaded on May 17,2022 at 10:02:12 UTC from IEEE Xplore. Restrictions apply.

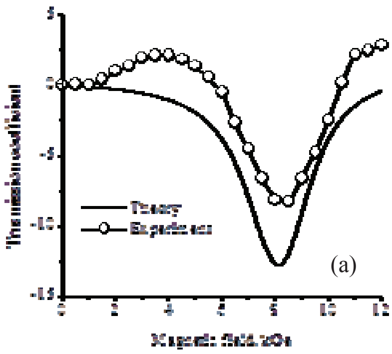

Fig. 5. Magnetic field dependencies of the relative refractive n' and absorption n'' indices of nanocomposite with Co particles: minimal the continuous line – theory calculated for f = 26 GHz, line with symbols – experiment.

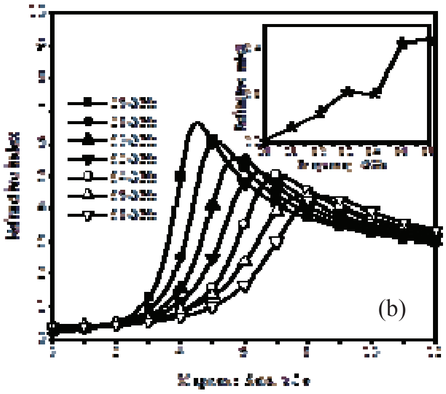

Fig. 6. Dependency of refractive index of the nanocomposite on magnetic field for several frequencies. In the insert the frequency of the dependence value of refractive index.

The further part of the paper concerns to the method of calculation of the transmission coefficient and its magnetic field dependency. The final objective of the calculation is the field dependences of the effective magnetic permeability and the refractive index. The conductivity σ= 0.364 S/m and the dielectric permittivity ε_1 = 3.29 for the Co-containing nanocomposite were defined from the frequency dependency of transmission coefficient without magnetic field. The thickness of the sample is $d = 1$ mm and the mass share of the ferromagnetic phase is assumed to be $m_F = 0.07$ as a mean value of the average ferromagnetic phase concentration. For the frequency $f = 26$ GHz the value of the dissipative parameter was chosen equal to $\alpha \approx 0.166$ in order to the linewidths of the calculated and experimental lines correspond each other. The comparison of the calculated and experimental dependences of the relative variations of the transmission coefficient module for the frequency of 26 GHz is shown in Fig.5.

Let us examine a supposition that the nanocomposite studied is a media with negative refractive index. The complex refractive index is defined by the relation $n = n' - in''$, where n' is the refractive index and n'' is the absorption coefficient. The dependences shown in Fig.6 represent the results of calculation of the complex refraction index on the submicron scale. The refractive index on the submicron scale is very spatially heterogeneous. One could believe that a low value of the refraction index at the submicron scale sized of several hundreds of nanometers and including a ferromagnetic particle gives an argument to suppose the nanocomposite studied as a media that on the submicron scale looks like the ENZ-media. The examination of the phase velocity however reveals the essential difference. The phase velocity of the electromagnetic wave in the nanocomposite is essentially less than the speed of light. Therefore the electromagnetic properties of the studied nanocomposite differ markedly from the ENZ-media.

The work was done within RAS Program (project No 01.2.006 13391), with partial support of NSh-6172.2012.2 grant.

REFERENCES

[1] A.B. Rinkevich, D.V. Perov, M.I. Samoilovich, and S.M. Klescheva, “Magnetic antiresonance in metamaterial based on opal matrix with metallic cobalt nanoparticles embedded,” *Metamaterials,* vol. 6, p. 27, 2012.

Authorized licensed use limited to: Ural Federal University. Downloaded on May 17,2022 at 10:02:12 UTC from IEEE Xplore. Restrictions apply.