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ALL-OPTICAL CHARACTERIZATION OF THE MAGNETIC PROPERTIES OF NANOCOMPOSITE BULK SAMPLE BASED ON FERRITES

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ABSTRACT

The magnetic properties of a nanocomposite bulk sample ($Ba_{0.5}Sr_{1.5}NiMgFe_{12}O_{22}$) were investigated in this paper from the perspective of its applications. All-optical magnetometry was used to characterize the sample. The electromagnetically induced absorption effect in a pump-probe configuration was exploited to produce magneto-optical resonances in a paraffin-coated rubidium vapor cell. The magnetic field created by the hard magnetic material was measured when the sample was positioned at different locations near the cell window. The results show that the optical system detected longitudinal and transverse magnetic fields caused by nanoparticles with randomized magnetic moments.

Keywords: coherent spectroscopy, electromagnetically induced absorption, all-optical magnetometry, nanoparticles, multiferroic, Y-type hexaferrite.

INTRODUCTION

The magnetic nanocomposites in recent years have seen growing application in the microwave components, such as for shielding of microwave radiation in medical research. Therefore, their magnetic properties must be thoroughly characterized, which requires the use of highly sensitive magnetometry. To evaluate the magnetic field created by randomized nanoparticles, we used an all-optical, non-invasive method based on coherent laser spectroscopy.

The electromagnetically induced absorption (EIA) magnetometer is one of the magneto-optical measuring methods that uses the interference between atomic sublevels of the sensor cell created after interaction with laser light [1, 2]. Magnetic fields (MFs) on the order of pT have been measured with this method. It has a wide range of applications in measuring of weak MFs, for example, remote magnetic field tomography, security applications [3].

In this research, we report a non-contact method for characterizing the magnetic properties of a nanocomposite bulk sample ($Ba_{0.5}Sr_{1.5}NiMgFe_{12}O_{22}$) in a polymer matrix (epoxy resin), according to the methodology of Alipieva et al. [4]. The hexaferrite $Ba_{0.5}Sr_{1.5}NiMgFe_{12}O_{22}$ is multiferroic with extraordinary properties. To use it as microwave absorbers we have to investigate the magnetic properties of these materials, incorporated in a nonmagnetic matrix. The goal is to measure the magnetic field created by the hard magnetic material, with a view to its applications [5].

EXPERIMENTAL

For the all-optical measurements of MFs, a layout of the experimental setup, presented in detail in [6], is shown in Fig. 1. The optical detector is a paraffin-coated Rb cell that has a cylindrical shape with a length of 25 mm and 20 mm diameter. To shield the laboratory magnetic fields, the cell was placed in two layers of μ-metal. The laser beam of the Fabry-Perot diode laser was passed through two polarization beam splitters (PBS) and mirrors (M) to form the pump-probe configuration. A solenoid was used to create a magnetic field B_{scan} collinear with the laser beams. The absorption of the probe beam was recorded as a function of the slowly changing magnetic field B_{scan}, scanned around its zero with a magnitude of ± 40 mG. The sample was positioned close to the cell window, as shown in Fig. 1 in three successive planes: XY - straight, facing the cell window; YZ - straight, transverse and ZX - lying down.

The composite pattern for the MF measurements was synthesized as a mixture of $Ba_{0.5}Sr_{1.5}NiMgFe_{12}O_{22}$ powder with average particles size around 500 nm. The $Ba_{0.5}Sr_{1.5}NiMgFe_{12}O_{22}$ powder was prepared by citrate sol-gel spontaneous combustion. The procedure started with mixing the respective metal nitrates; solution of citric acid ($C_6H_8O_7$) was carefully introduced to the mixture as a chelating agent, thus forming a homogenous solution with the metal cations. At 120ºC by slow dehydration, it was converted to a dark brown bulk, which self-ignited afterward and burned. The spontaneously combusted powders were annealed at 600ºC. The precursor powders thus produced were homogenized and retained in an oven at 1170ºC for five hours in air to obtain the material of desired composition $Ba_{0.5}Sr_{1.5}NiMgFe_{12}O_{22}$. The hexaferrite powders were dispersed homogeneously in the polymer matrix (epoxy resin). The inset in Fig. 1 shows the photograph of the nanocomposite sample, which has a diameter of 11.5 mm and an average thickness of 4.2 mm.

RESULTS AND DISCUSSION

The proposed all-optical method allows us to measure both longitudinal and transverse magnetic fields [4, 7]. The sensitivity of the method strongly depends on the accurate determination of the position of the EIA resonance on the magnetic scale and its width.

As a first point, we will discuss the results when the optical system was detected a longitudinal (B_z) magnetic field created by the hard magnetic material. In this case, the magnetic moment of the composite material is parallel to the scanned MF and only shift the position of the EIA resonance along the magnetic scale. The half difference between the resonance positions on the magnetic scale gives us the value of the measured MF.

Figs. 2 and 3 show the recorded signals for two locations of the sample: in the ZX and YZ planes, respectively.

As can be seen from Fig. 2, the measured MF created by the composite material lying in ZX-plane is $B_z = (5.12 \pm 0.21)$ mG. Almost the same is the MF generated by the sample when it is straight in the plane YZ, $B_z = (5.41 \pm 0.21)$ mG, (Fig. 3). When the pattern was placed in the XY-plane, a larger shift of the resonance position on the magnetic scale was observed (not shown here) and $B_z = (6.56 \pm 0.21)$ mG was measured.

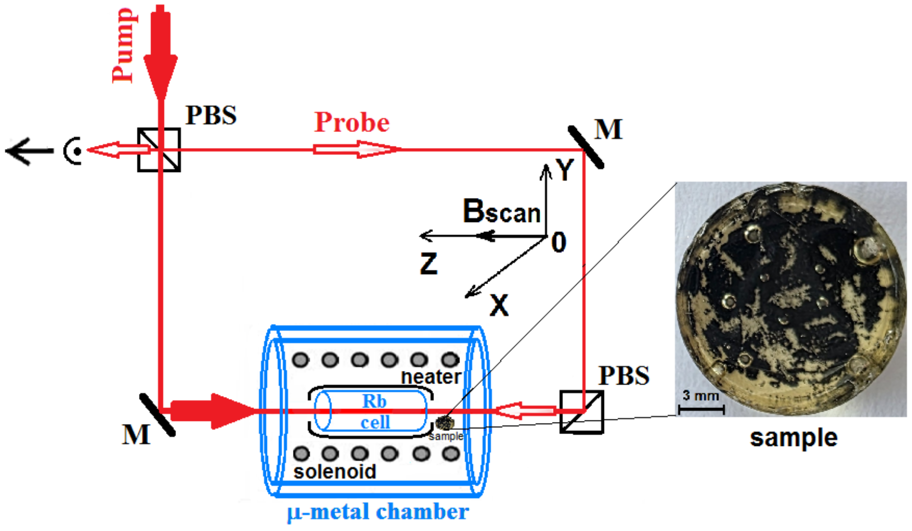
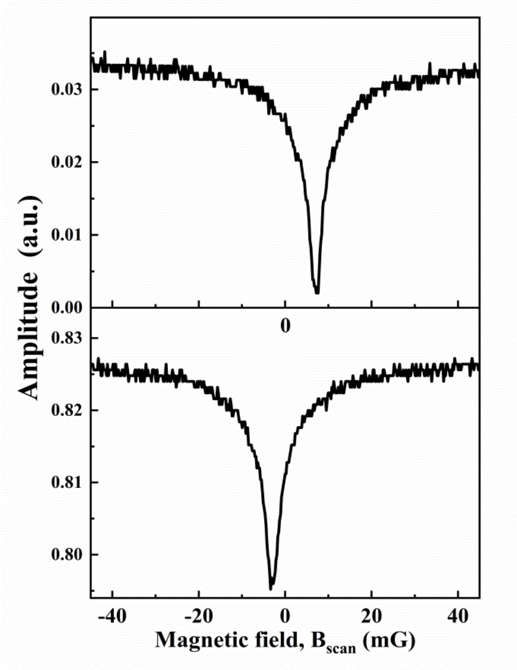


Fig. 1. Geometry of the experiment and photo of the nanocomposite bulk sample ($Ba_{0.5}Sr_{1.5}NiMgFe_{12}O_{22}$) as an inset on the right: PBS - polarizing beam splitter; M - mirror.



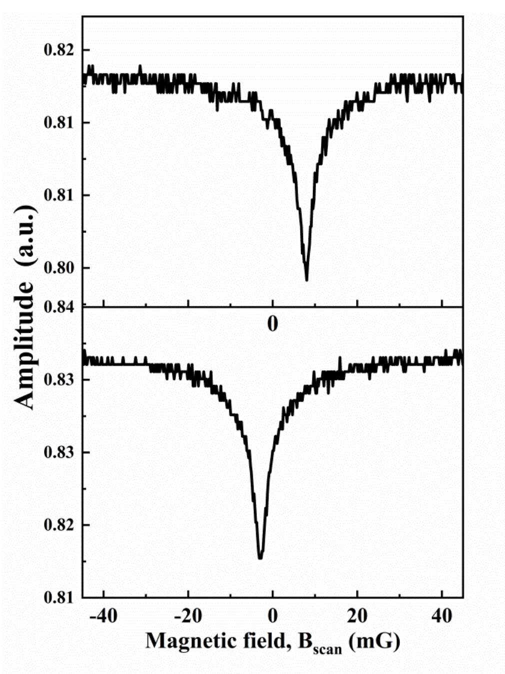
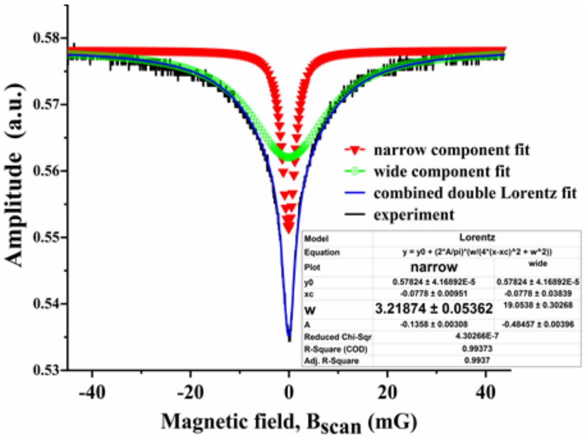
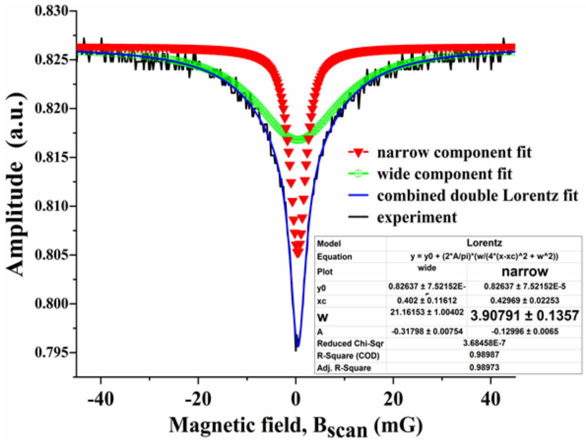


Fig. 2. The resonance positions for both directions of B_{scan}. The sample lies in the ZX-plane.

Fig. 3. The resonance positions for both directions of B_{scan}. The sample is straight, in the YZ-plane.



Model	Lorentz	
Equation	y = y0 + (2*A/pi)*(w/(4*(x-xc)^2 + w^2))	
Plot	narrow	wide
y0	0.57824 ± 4.16892E-5	0.57824 ± 4.16892E-5
xc	-0.0778 ± 0.00951	-0.0778 ± 0.03839
w	3.21874 ± 0.05362	19.0538 ± 0.30268
A	-0.1358 ± 0.00308	-0.48457 ± 0.00396
Reduced Chi-Sqr	4.30266E-7	
R-Square (COD)	0.99373	
Adj. R-Square	0.9937	



Model	Lorentz	
Equation	y = y0 + (2*A/pi)*(w/(4*(x-xc)^2 + w^2))	
Plot	wide	narrow
y0	0.82637 ± 7.52152E-5	0.82637 ± 7.52152E-5
xc	0.402 ± 0.11612	0.42969 ± 0.02253
w	21.16153 ± 1.00402	3.90791 ± 0.1357
A	-0.31798 ± 0.00754	-0.12996 ± 0.0065
Reduced Chi-Sqr	3.68458E-7	
R-Square (COD)	0.98987	
Adj. R-Square	0.98973	

Fig. 4. The reference resonance width without the sample.

Fig. 5. The broadened EIA resonance. The sample is lying in plane ZX.

In the next point, we will present results for the measured transverse (B_{tr}) magnetic fields registered by the rubidium sensor. In this case, the magnetic moment of the composite material is transverse to the laser beams and increases the width of the EIA resonance.

Fig. 4 shows the results of the fitting of the control EIA resonance, i.e. the signal without the sample with a compensated transverse magnetic field. The signal has a two-component structure due to the physical processes that form the resonance. Here, we will use only the narrow component (triangle points, upper curve) of the EIA resonance for greater measurement accuracy. The full width at half maximum (FWHM) of the narrow component is W_{narrow} = (3.22 ± 0.05) mG.

For a weak transverse magnetic field B_{tr} created by the pattern located in the ZX-plane, the FWHM of the narrow component is W_{narrow} = (3.91 ± 0.14) mG, as shown in Fig. 5. The broadening of the resonance signal confirms that the magnetic moment of the composite material is transverse to the probe and pump beams. The experimental results present that the hard magnetic material was created transverse magnetic field

B_{tr} = (0.69 ± 0.09) mG. When the sample is positioned in the YZ and XY-planes, it creates a smaller MF, B_{tr} = (0.2 ± 0.1) mG and B_{tr} = (0.29 ± 0.2) mG, respectively.

CONCLUSIONS

The presented results demonstrate that the proposed all-optical method allows the measurement of a weak magnetic field created by $Ba_{0.5}Sr_{1.5}NiMgFe_{12}O_{22}$ nanoparticles with randomized magnetic moments. The MF generated by a hard magnetic material was measured when the sample was situated sequentially in front of the optical detector in the planes XY, YZ and ZX. In the three different positions, a longitudinal MF of the same order of magnitude $B_z \sim 5$ mG was measured, while the measured transverse magnetic field B_{tr} was smaller, a few tenths of mG. The experiment proves that this method enables the evaluation of the magnetic fields created by hard magnetic materials for various applications. The main applications of these composite samples are in microwave technic - like absorbers and antireflection layers.

Acknowledgments

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Authors’ contributions

All authors planned the objectives of the experiment. S.K. and T.K. prepared the nanocomposite sample. E.T. performed the measurements and wrote the manuscript.

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