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Physics

INVESTIGATION OF EFFICIENCY OF NONLINEAR INTERACTION OF ELECTROMAGNETIC WAVES IN THE FERROMAGNETIC

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The efficiency of detection of laser radiation in the magnetized transparent ferromagnetic materials was investigated. The nonlinear interaction of electromagnetic waves in the ferromagnetic for the different forms of the magnetization curve of a ferromagnetic in MatLab environment was modeled. It is shown that the detection of amplitude modulated electromagnetic radiation can be obtained as a result of such nonlinear interaction. The magnitude and sign of detected signal greatly depends on the shape of the magnetization curve and on the applied external magnetic field. The simulation results for the samples of monocrystalline yttrium iron garnet are well correlated with the experimental results.

Keywords**:** nonlinear interaction, detection, ferromagnetic, magnetic field, magnetization.

Introduction. Nonlinear properties of ferromagnetics in the low-frequency and RF range are well investigated and are widely used in electronics. Ferromagnetics are one of the basic materials for the recording and storage of information. The detectors, frequency converters, amplifiers, limiters, etc. on their basis were developed [1–3].

Ferromagnetic materials that are transparent in these areas are widely used in the infrared and optical regions for rotating of polarization plane, radiation control, etc. The various optoelectronic devices were created on the base of these ferromagnetics. There are a lot of studies (see., for example, [4–7]) demonstrating the possibility of reorientation of the magnetic moment of optically transparent ferromagnetic materials under the influence of ultra-short laser pulses that can be used for fast data recording and playback.

So far, it is considered that in the optical range magnetic permeability of ferromagnetic materials is equal to one, so, the above phenomena can not be connected with the magnetic nonlinearity. It is assumed [7] that the origin of the observed ultrafast ferromagnetic magnetization reorientation can be explained by the emergence of nonlinear dielectric susceptibility in the optical region. But the emergence of nonlinear dielectric susceptibility of a ferromagnetic in an external magnetic field is not physically justified. This description is purely phenomenological. The

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interpretation of the ultrafast magneto-optical response of ferromagnetic materials is still the subject of debate.

However, in [8, 9] the detection of the linearly polarized amplitude-modulated laser radiation in the transparent ferromagnetic monocrystalline yttrium iron garnet (YIG) at room temperature was experimentally obtained. Based on the fact that the dependence of detected signal parameters on external magnetic field is well correlated with the magnetization curve of the used ferromagnetic, the authors suggest that the detection is obtained as a result of the nonlinear interaction of laser radiation with the ferromagnetic.

In the present paper the magnetization curves of different samples of YIG monocrystal used for the detection of electromagnetic waves was investigated. Samples were fitted with various systems for the registration of the change of the magnetic moment. The dependence of the efficiency of the nonlinear interaction of electromagnetic waves on the shape of the magnetization curve was considered.

Magnetization Curve of Monocrystallic YIG Ferromagnetic. In [8–9] for the detection of infrared laser pulses the classical ferromagnetic YIG monocrystals were used. The monocrystallic YIG is a soft ferromagnetic (without hysteresis), which have a transparency window in the wavelength region 1.1–5.5 μm (absorption coefficient $\beta \approx 0.05\ cm^{-1}$), and is partially transparent in the region of 0.9–1.1 μm ($\beta \approx 15\ cm^{-1}$).

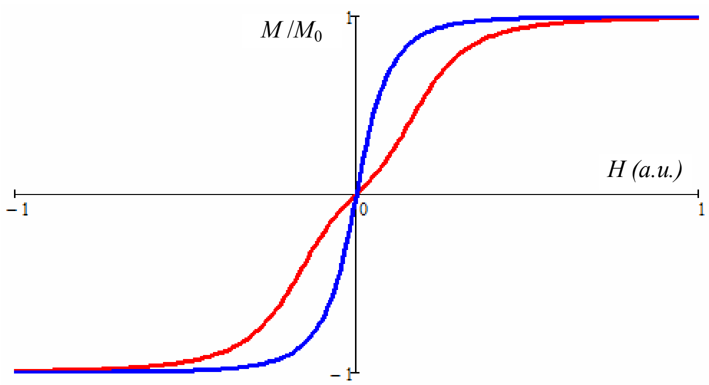

Fig. 1. Typical forms of magnetization curve of soft ferromagnetic materials.

The magnetization curve of such monocrystals may have various shapes, which depends on the composition and form of the sample. Typical shapes of magnetization curve are shown in Fig. 1. The saturation magnetization is:

$$4\pi \mathbf{M}_0 \approx 1750\, Gs.$$

Different magnetic sensors representing a horseshoe ferrite body with a coil inductor wound around it was used for registration of the average magnetic moment changes of the magnetized YIG sample (Fig. 2, A). The cross-sectional area of horseshoe ferrite initially was selected sufficiently large, so that, in case of YIG sample saturation the horseshoe ferrite will be away from saturation. The shape of the magnetization curve of the sample essentially depends on the parameters of ferrite sensor. For this reason, the magnetization curve YIG sample each time was measured with the ferrite sensor.

In Fig. 2, B the block diagram of experimental setup for measurement of magnetization curve is presented. Measurements were carried out indirectly in the following way: on a system with the YIG sample and the horseshoe ferrite a transformer was constructed.

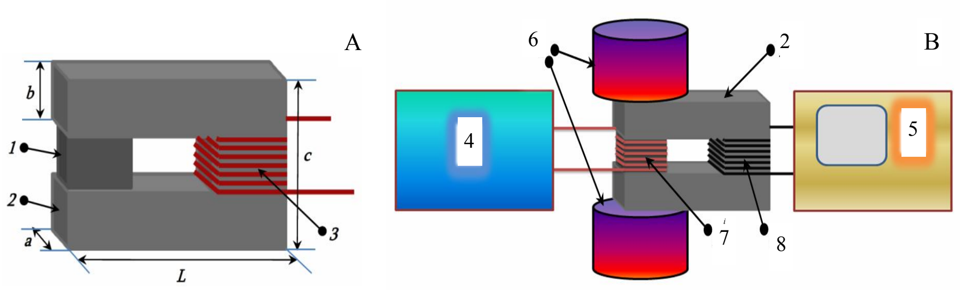

Fig. 2. A. YIG sample with magnetic sensor.
B. The block diagram of experimental setup for measurement of magnetization curve of YIG sample.

1 – YIG sample;	5 – transformer;
2 – horseshoe ferrite body;	6 – oscilloscope;
3 – coil inductor;	7 – primary winding;
4 – sinusoidal voltage generator;	8 – secondary winding.

From standard generator an alternating (sinusoidal) voltage with $f = 1$ *kHz* frequency on the primary winding $(n_1 = 300)$ of transformer was applied, which creates an alternating magnetic flux in the core and induces an alternating electromotive force (voltage) in the secondary winding $(n_2 = n_1)$. The secondary winding are wrapped around a core (ferrite) with high magnetic permeability $(\mu \approx 2000)$, so that, all of the magnetic flux passes through the secondary windings. Signal in the secondary winding was registered by an oscilloscope. YIG sample with magnetic sensor were placed in the external controllable magnetic field, which can be changed in the range of 0–1 *kOe*.

The amplitude of the induced voltage on the secondary winding, depending on the external magnetic field was measured when the amplitude of the voltage on the primary winding was constant.

It is not difficult to see, that the amplitude of the measured voltage is directly proportional to the differential permeability of the YIG sample. Indeed the differential permeability is defined as the permeability of a material to a low AC magnetic field H_{AC} superposed on a DC magnetic field H_0 $(\mathbf{H} = \mathrm{H}_{AC} + \mathrm{H}_0)$:

$$\mu'(H_0) = \left.\frac{dB}{dH}\right|_{\mathbf{H}=\mathbf{H}_0}, \quad (1)$$

where B is the magnetic induction (magnetic flux density), *Gauss (Gs)*; H is magnetic field intensity, *Oersted (Oe)*.

Thus, by measuring of the dependence of amplitude of the induced voltage on the secondary winding on the external magnetic field one can found the differential permeability of YIG sample, consequently the slope of a tangent to the *M–H* curve. Considering that the saturation magnetization of YIG is M = 1750 *Gs*, can be recovered *M–H* curve.

The results of measurements for the monocrystalline YIG sample with dimensions $0.4\times5\times6.5$ mm^3, and $a = b = 2.75$ mm, $c = 12$ mm, $L = 10$ mm for ferrite (see Fig. 2, A) are shown in the Fig. 3.

Efficiency of Nonlinear Interaction of Electromagnetic Waves in the Ferromagnetic. The detection process of amplitude modulated electromagnetic radiation was modeled in MatLab environment for the evaluation of efficiency of nonlinear interaction of electromagnetic wave in the YIG ferromagnetic. In the modeling the magnetization curve by the analytic function $f = A\ \mathrm{arctg}(\alpha H + \beta H^3)$ were approximated. If the value of $\alpha = 0.4$, $\beta = 0.23$ and A=1066 Gs, the simulated curve with accuracy of ≈5% coincides with experimentally curve (see Fig. 4). It is natural to assume that in case of a zero external magnetic field should not expect the detection of electromagnetic waves due to nonlinear interaction.

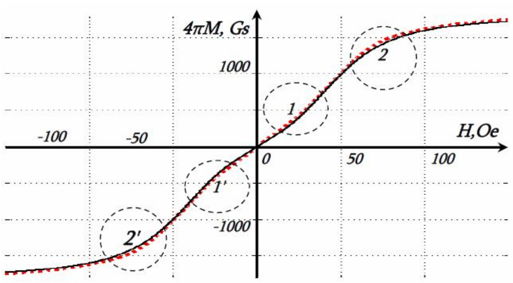

Fig. 3. Magnetization curve for the monocrystalline YIG sample with the ferrite sensor: dot line – experiment; solid line – approximation.

Based on the obtained magnetization curve of the YIG, effective detection can be expected near the value of the external magnetic field $H_{01} \approx \pm 30$ Oe (section 1, 1', where the rate of increasing of the magnetization curve slope is the highest) as well as in $H_{02} \approx \pm 60$ Oe (section 2, 2', here the magnetization curve is near to saturation and the slope decreases rapidly).

Indeed, simulation results indicate that detected signal initially increases with increasing of the external magnetic field, reaches a maximum, decreases to zero, changes polarity and again begins to increase to the next maximum (see Fig. 4).

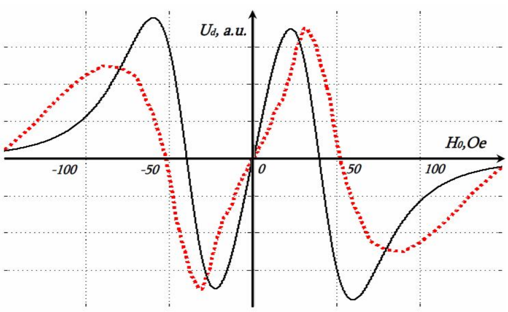

Fig. 4. Dependence of the detected signal magnitude on the external magnetic field: dot line – experiment; solid line – simulation result.

With further increase of the external magnetic field, the magnetization curve is gradually saturated and amplitude of the detected signal seeks to zero.

In Fig. 4 it is also presented the curve of dependence of the detected signal magnitude on the external magnetic field, obtained experimentally in case of laser pulses detection. The comparison shows that these curves are completely consistent with each other by their behavior. The deviation of the position of maximum and minimum values of detected signal may be associated with the large amplitude of the magnetic field of the laser pulse. At large amplitudes of the magnetic field of the laser radiation, when the changes of external magnetic field in a certain area the nonlinear region 1 (1'), as well as region 2 (2') of the magnetization curve (Fig. 3) can impact on the detection process.

The abovementioned impact surely will change the quantities and positions of the maximum and minimum values of the resulting signal.

Conclusion. The efficiency of optical detection of infrared laser pulses in the monocrystallic YIG ferromagnetic was investigated. It is shown that the efficiency of the nonlinear interaction strongly depends on the shape of the magnetization curve of ferromagnetic sample.

The parameters of the detected signal, as a function of the external magnetic field, are well correlated with the magnetization curve of the YIG sample.

Analysis of the plots shown in Fig. 4 suggests that, in the absence of an external magnetic field, the laser radiation causes the magnetic moment to oscillate around zero and, thus, its average value does not change and the detected signal is zero. Upon the application of a magnetizing external magnetic field, the detected signal is still zero as long as the magnetization curve remains linear. Detected signal initially increases with increasing of the external magnetic field, reaches a maximum, when the magnetization curve has the maximum nonlinearity. Near of turning point of the magnetization curve the signal reaches to zero. With the increasing of the external magnetic field the detected signal changes polarity and again begins to increase to the next maximum (Fig. 4). At full saturation, the reorientation of the magnetic moment hardly occurs under the action of laser radiation, which leads to a drop in the amplitude of the detected signal.

The results of this study may find applications, e.g., for the frequency conversion of laser radiation, for optical recording, storage, and signal processing.

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