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Investigation of the Detection of Infrared Laser Radiation in Monocrystalline Yttrium Iron Garnet

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Abstract. The results of research of detecting the infrared laser radiation in transparent ferromagnetic yttrium iron garnet (YIG) at room temperature are presented. It is shown that the magnitude and sign of the detected signal depend essentially on the external magnetic field and the shape of magnetization curve of the ferromagnetic. The dependence of detected signal on applied magnetic field is in good agreement with static magnetization curve of the ferromagnetic sample. The detected signal is different from zero only for those values of the external magnetic field at which the magnetization curve of ferromagnetic sample is nonlinear. The detection process of an amplitude modulated electromagnetic radiation was modeled in MATLAB environment. It is shown that at the low power of laser radiation the magnitude of the detected signal linearly dependents on the laser power, which is confirmed by the experimental results.

Keywords: magnetic moment, magnetic field, magnetic nonlinearity, magnetization curve, detection

1. Introduction

Ferromagnetic materials are widely used in electronics as the cores of transformers, throttles and electromagnets, and as permanent magnets in electric motors and generators. In addition, ferromagnetics are one of the basic materials for the recording and storage of information. They are also widely used in the microwave, infrared and optical regions for rotating the plane of polarization of light, for radiation control, etc. [1-2].

It is also well-studied nonlinear magnetic properties of ferromagnetic materials in the low frequency and radio frequency, as well as is widely used in electronics. The detectors, frequency converters, amplifiers, limiters have been developed based on ferromagnetic materials ([3-4]).

There are many studies (see e.g. [5-9]), indicating the possibility of a reorientation of the magnetic moment of ferromagnetic materials under the influence of ultra-short laser pulses, which can be used for the fast data recording and playback.

In [10,11], the detection of linearly polarized amplitude-modulated laser radiation in the infrared transparent ferromagnetic yttrium iron garnet (YIG) at room temperature was experimentally obtained and suggested the qualitative interpretation mechanism of the nonlinear interaction. Measurements of dependence of the amplitude of the detected signal on the angle between the laser polarization vector and the magnetization vector of the ferromagnetic sample confirm the proposed mechanism of occurrence of nonlinearity. However, the interpretation of the magneto-optical response of ferromagnetic materials is still the subject of debate.

2. Motion of magnetic moment in an alternating magnetic field

Usually, to describe the magnetization of the ferromagnetic medium in an alternating magnetic field is used the equation of motion (1) of the magnetic moment in a constant magnetic field [12, 13] (Larmor's theorem) with various dissipative terms **R** [12-14]:

$$\frac{d\mathbf{M}}{dt} = -\gamma[\mathbf{M}\times\mathbf{H}] + \mathbf{R}\,, \qquad (1)$$

where **M** is magnetic moment, **H** – constant magnetic field, γ– gyromagnetic ratio.

Equation (1) is substantially nonlinear. However, it is not applicable to describe the motion of the magnetic moment in an alternating magnetic field, because it does not describe the excitation of the magnetic moment due to the time dependence of the magnetic field.

Taking into account the changes of the magnetic field in time, the equation of motion of magnetic moment should be written in the form in which there is a member responsible for the excitation of the magnetic moment due to alternating magnetic field [10]:

$$\frac{d\mathbf{M}}{dt} = -\gamma[\mathbf{M}\times\mathbf{H}] - \gamma^2 I\frac{d\mathbf{H}}{dt} + \mathbf{R}\,, \tag{2}$$

where I is the moment of inertia.

From equation (2) follows that in an oscillating magnetic field, the magnetic moment along with attenuating precession, also performs oscillating motion with the frequency of the alternating magnetic field. The amplitude of the oscillations of the magnetic moment of the sample depends on the slope of the magnetization curve for a given value of an external constant magnetizing field.

Since when the external magnetic field is changing, the magnetization curve slope varies, so it is expected that values of the external magnetic field, the magnetic moment of the ferromagnetic will perform nonlinear oscillations.

In this paper, we investigate the detection of low-power laser infrared radiation in YIG monocrystal obtained as a result of nonlinear excitations of the magnetic moment of the sample by the magnetic field of the laser radiation. In addition, it was considered the dependence of the efficiency of detection on the shape of the ferromagnetic magnetization curve and the power of the laser radiation.

3. Experimental setup and the results of measurement

The block diagram of the experimental setup is shown in Figure 1.

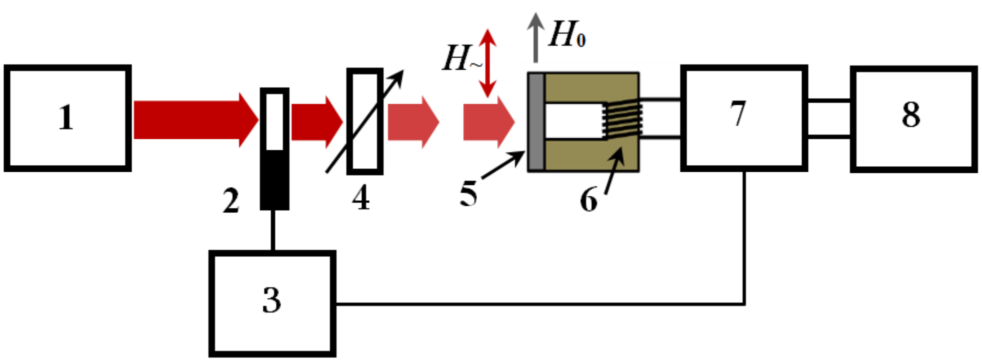

Fig.1. The experimental setup: 1. LG-126 HeNe laser, 2. Mechanical chopper, 3. Controller of the mechanical chopper, 4. Variable optical attenuator, 5. YIG sample, 6. Ferrite sensor (horseshoe shaped ferrite with a coil inductor), 7. Lock-in amplifier (Stanford Research System SR510), 8. Oscilloscope (Agilent Technologies DSO7012B).

As a source of infrared radiation, the HeNe continuous laser was used. The laser parameters were as follows: wavelength $\lambda \approx 1.15\mu m$, polarization of radiation - linear, the output power $P \approx 12mW$, beam – Gaussian with the diameter of $d \approx 7mm$.

As the ferromagnetic material, the monocrystalline YIG samples were used. Monocrystalline YIG well suited for our investigation because it has transparency window in the wavelength range 1.1-5.5μm [15]. The absorption coefficient in the transparency window $\beta \approx 0.03$ - 0.1 cm^{-1}. For our samples at the wavelength $\lambda \approx 1.15$ μm it was $\beta \approx 0.1$ cm^{-1}. Saturation magnetization of YIG at room temperature – $4\pi M_0 \approx 1750$ G, the Curie temperature – $T_C = 556\ K$.

To register the detected signal (change of the average value of the magnetic moment of the magnetized YIG sample under the influence of modulated electromagnetic radiation) magnetic sensor 6 representing a horseshoe shape ferrite with the coil inductor was used (see Fig. 1). However, upon detection of a continuous laser radiation, this sensor cannot register the signal without modulation of the laser radiation. Therefore, the low-frequency (1 *kHz*) modulation of the HeNe laser radiation with a mechanical chopper 2 was performed for registration of the change of the magnetic moment. Modulated laser beam was directed to the ferromagnetic sample YIG. The ferromagnetic sample was located in the path of the laser radiation in such a way that the direction of the magnetic moment of the sample, magnetized in the external field H_0, coincides with the direction of the magnetic field $H_\sim$ of the linearly polarized laser radiation (see Fig. 1). As follows from the equation of motion of the magnetic moment (2), this arrangement may lead to the excitation of the magnetic moment of magnetized ferromagnetic under the influence of electromagnetic wave.

The change in the magnetic moment of the YIG crystal excites EMF in the coil inductor of magnetic sensor (detected signal), which is amplified by the lock-in amplifier 7 and recorded with an oscilloscope 8.

Figure 2a shows the dependence of M on the magnetizing magnetic field H_0 for YIG sample with dimensions of 0.4 x 5 x 6.5 mm^3 with a ferrite sensor. In Figure 2b the corresponding curve for dependence of the detected signal on H_0 is shown. It should be noted that the shape of the magnetization curve of YIG sample significantly depends not only on the geometrical shape and dimensions of the sample itself, but also on the parameters of the ferrite sensor.

Graphs in Figure 2 show that the detected signal is absent at zero external magnetic field. The detection occurs in the nonlinear region of magnetization curve of the ferromagnetic sample.

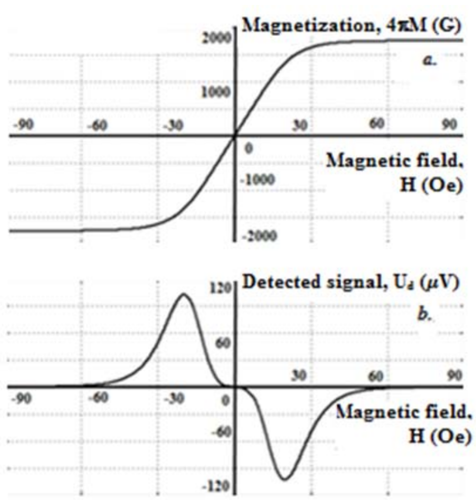

Fig. 2. a – the magnetization curve, b – dependence of the magnitude of detected signal on the external magnetic field.

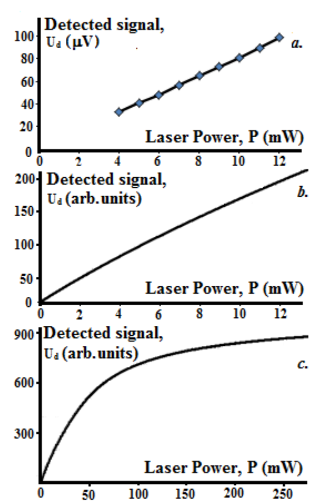

Fig. 3. Dependence of the detected signal on the laser radiation power.

The detected signal reaches its maximum value at the external field $H_0 \approx 25$ Oe and equals to ~100 μV (~0.3 μV per winding) when the power of laser radiation is *~12mW*. We have also investigated the dependence of the detected signal on the power of laser radiation at the external magnetizing field $H_0 = 25$ *Oe*. With decreasing the laser radiation, the power of detected signal decreases proportionally to the radiation power (Figure 3). This implies that we have the quadratic dependence of the magnetic moment of the sample on the magnetic field near the value of $H_0 = 25$ *Oe*.

For the evaluation of the efficiency of nonlinear interaction of electromagnetic wave in the YIG ferromagnetic depending on the external magnetic field H_0 and the laser intensity, the detection process of amplitude modulated electromagnetic radiation was modeled in MATLAB environment.

In the simulation the magnetization curve of YIG sample was approximated with the function $4\pi M = A\cdot tan^{-1}(\alpha H + \beta H^3 + \chi H^5)$, which coincides with the experimentally obtained curves with accuracy up to 5% for the following values of coefficients: A, α, β, and χ : A=1114 G, α= 0.05, β = $4.13\cdot10^{-5}$, $\chi = 4.06\cdot10^{-8}$.

Simulation results show that at the relatively low power ($H_\sim << H_0$) the dependence of the magnitude of the detected signal on the laser power is similar to the experimentally obtained results (see Figure 3a, b). However, in the case of high-power of laser radiation ($H_\sim \geq H_0$), the dependence changes cardinally (Figure 3c).

4. Discussion of the Results and Conclusions

Thus, we experimentally obtained the detection of linearly polarized low-power laser radiation in the transparent ferromagnetic YIG at room temperature. The results of investigations show that the magnitude and sign of the detected signal well correlated with the static magnetization curve of ferromagnetic sample.

At the small values of the external magnetic field ($H_0 \leq 10$ *Oe*), where the curve is nearly linear, no detection was observed. Effective detection was obtained in the range of maximum nonlinearity of the magnetization curve. With further increase of the external magnetic field, the magnetization curve gradually becomes saturated, and the amplitude of the detected signal tends to zero.

In our experiments, HeNe laser with a maximum power of 12 *mW* was used. When the beam is focused on the YIG crystal, the diameter of laser beam amounted to ~5 *mm*, which corresponds to the beam intensity of ~60 mW/cm^2 and to the magnetic field strength $H_\sim \approx 0.02$ *Oe*.

The modeling shows that for such values of the magnetic field $H_\sim$ the dependence of the detected signal on the laser power is linear (Figure 3b), which is confirmed by the experimental results. With the increase of laser radiation power, the linear relationship is broken and the conversion efficiency decreases gradually since the change of the magnetic field occurs outside of the nonlinear area of magnetization curve.

In conclusion, we note that presented results can be used at the detection and conversion of frequencies of electromagnetic radiation for the optical recording, storage, processing of information, etc.

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