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Investigation of Detection of Microwave Radiation in Ferromagnetic YIG

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Abstract. The detection of amplitude-modulated microwave radiation (1.07-2.14 GHz) in the ferromagnetic yttrium iron garnet (YIG) at room temperature was experimentally obtained. The detected signal (the change of magnetic moment of YIG sample under the influence of microwave magnetic field) was recorded by the magnetic sensor representing a horseshoe-shaped ferrite with an inductor. It is shown that the magnitude and sign of the detected signal depend essentially on the slope of the magnetization curve (on the differential magnetic permeability) and on the bias magnetic field (on the bias current of the magnetizing coil). The dependence of the magnetic permeability and the detected signal on the bias current shows that they have hysteretic behavior. The dependence of detected signal on applied magnetic field (bias current) is in good agreement with static curve of differential magnetic permeability of the ferromagnetic sample.

Keywords: Microwave field, magnetic moment, nonlinearity, magnetization curve, differential magnetic permeability

1. Introduction

The properties of ferromagnetic materials in the microwave field were extensively studied at the beginning of the last century, after the experimental detection of ferromagnetic resonance. In the works of the first period, the linear phenomena have been investigated in ferrite during the interaction of relatively weak microwave fields, on which numerous ferrite devices were created. They are widely used in radar, radio astronomy and in other areas of electronics and experimental physics. During review of working principle of linear ferromagnetic devices, in the first approximation, tensor components of the magnetic susceptibility can be considered independently on the amplitude of the alternating field. These components are determined by solving the equation in the linear approximation.

However, in the case of arbitrary amplitudes of the alternating magnetization, Landau-Lifshitz equation is significantly nonlinear. First, nonlinear phenomena in ferromagnetic materials in the microwave region were discovered by Bloembergen and Damon [1] (in a nickel-ferrite powder in the field of magnetron radiation with a frequency $f \cong 9$ GHz). Later, number of works related to the generation, detection, frequency conversion and amplification of microwave radiation using ferromagnetic materials was published (see for example [2, 3]). These nonlinear phenomena principally occur at any amplitudes of the microwave field, but being a quadratic effect, affect only at sufficiently large fields. These nonlinear phenomena described by the Landau-Lifshitz equation, occur only in the presence of the perpendicular component of the microwave field, relative to the direction of the constant magnetization field of a ferromagnetic. According to the Landau-Lifshitz equation, in case of a parallel orientation of the alternating magnetic field, with respect to the magnetic moment, the interaction cannot take place between microwave signal and ferrite.

However, there are many works, in which the magnetic moment changes of the ferromagnetic sample under the influence of a linearly polarized electromagnetic radiation were demonstrated. For example, in [4-6] experimentally obtained the detection of linearly polarized amplitude-modulated laser radiation in near- and far-IR regions in transparent ferromagnetic samples at room temperature, when the magnetic field of radiation is oriented parallel to the magnetization of the sample. In [7-10] the possibility of reorientation of the magnetic moment of optically transparent ferromagnetic materials under the influence of ultra-short laser pulses was shown. In [8] is assumed that the ultrafast reorientation of the magnetization of a ferromagnetic can be explained by the emergence of the nonlinear dielectric susceptibility in the optical region. However, this explanation is purely phenomenological and physically is not justified. In [4] a mechanism to explain the nonlinear interaction of electromagnetic radiation with a magnetized ferromagnetic is proposed. The experimental results presented in [4-6] (the dependence of the amplitude of the detected signal on the angle of the laser polarization, polarity reversal, as well as the presence of the detected signal peaks) are in good agreement with the proposed mechanism of occurrence of non-linearity. Although it is generally considered that the above mentioned phenomena cannot be related with a magnetic nonlinearity of ferromagnetic, because in the optical region magnetic permeability of ferromagnetic materials is practically equal to one. Therefore, the interpretation of ultrafast magneto-optical response of ferromagnetic materials is still the subject of discussions.

In this paper, the detection of low-power electromagnetic radiation of microwave region (1.07-2.14 GHz) in a magnetized ferromagnetic material was obtained, when the magnetic field of microwave radiation is in collinear arrangement with magnetization of ferromagnetic material. The dependence of the detected signal on parameters of microwave signal and on the characteristics of the ferromagnetic sample was investigated.

2. Experimental setup and the results of measurement

The block diagram of experimental setup is shown in Fig. 1. From the sweep generator 1 (P2-52) modulated RF signal (100 kHz modulation frequency) was fed to the coil 3 wound around the investigated ferromagnetic sample 2 (see Figure 1). As a non-linear ferromagnetic sample the polycrystalline YIG with rectangular shape by dimensions of 13×3.5×1.5 mm^3 was used. To register the detected signal (the change of the average value of the magnetic moment of the sample under the influence of the microwave field) the magnetic sensor 4 in the form of a horseshoe ferrite with inductor 5 wound around ferrite was attached to the ferromagnetic sampleas illustrated in Fig. 1. Such arrangement of ferrite sensor reduces demagnetizing factors of ferromagnetic sample, which in turn causes increases system sensitivity.

The magnetization of ferromagnetic sample was produced by passing current through the recording coil 5, similarly to the method described in [5]. The low-frequency ferrite brand 2000 NM was used as a magnetic sensor. To prevent its saturation during the magnetization of YIG sample, the cross section of horseshoe-shaped ferrite was chosen much larger than the cross-section of YIG sample. For decoupling the registering unit from regulated DC voltage source 7, the throttle (inductor with L = 200mH) was used. R = 10 Ohm ballast resistor that is connected in series with the inductor L, limits the maximum DC through the recording (magnetizing) coil 5. The total direct current resistance was 143 Ohm. In such configuration of the ferromagnetic sample and sensor, the microwave magnetic field proves to be parallel to the constant magnetizing field.

One of the important characteristics of magnetic materials is the magnetization curve, which may have different forms, depending on the composition, size and shape of the sample, as well as on the magnetic properties of the environment.

The magnetization curve is completely described by the differential magnetic permeability of the sample:

$$\mu'(H_0) = (dB/dH)\,|_{H=H_0}, \tag{1}$$

which essentially depends on the parameters of the sample, as well as on the parameters of the ferrite sensor. For that reason, we measured the differential magnetic permeability of the YIG sample with the ferrite sensor depending on the magnetizing field (bias current of magnetizing coil 5).

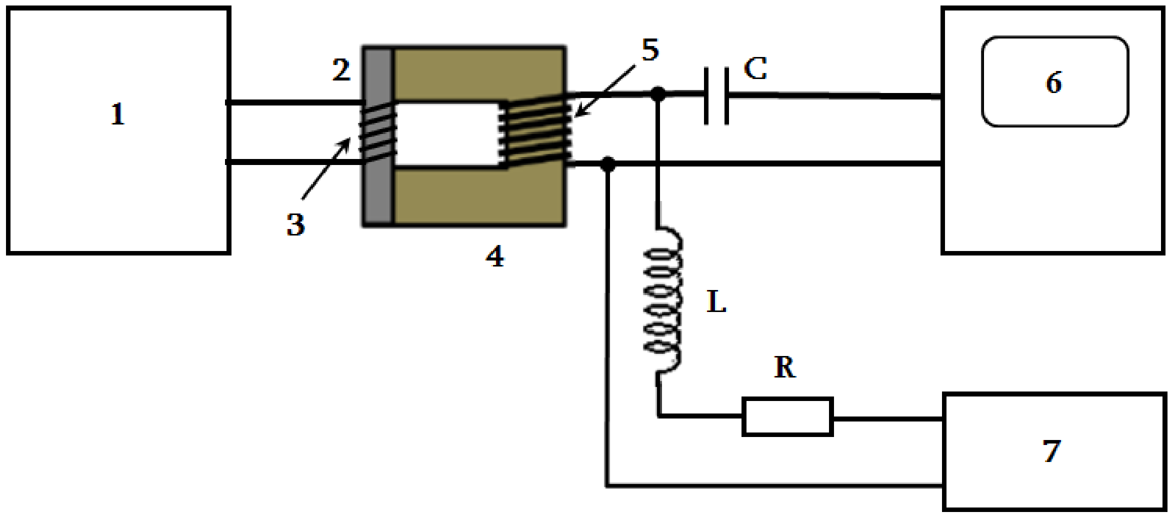

Figure 1. The experimental setup: 1. Microwave sweep generator, 2. YIG sample, 3. Primary coil, 4. Horseshoe shaped ferrite, 5. Secondary coil (for sensing and bias magnetization), 6. Oscilloscope, 7. Adjustable DC source, C – decoupling capacitance, L – decoupling inductor, R – ballast resistor.

Measurements were performed as described in [6]. The measurement results are presented in Figure 2, which shows that the curve has a hysteretic character. Measurements were made both in the sweep mode (sweep range is 1.07-2.14 GHz) and for a separate fixed frequency. The detected signal produced at the output of the magnetic sensor (inductor 5) was registered by the oscilloscope 6 (Agilent Technologies DSO7012B).

It should be noted that the detection had the non-resonant character and was not observed any features over the entire range of the microwave generator (1-2GHz). The results of the measurements for the frequency of 1.1 GHz are shown in Fig. 2b.

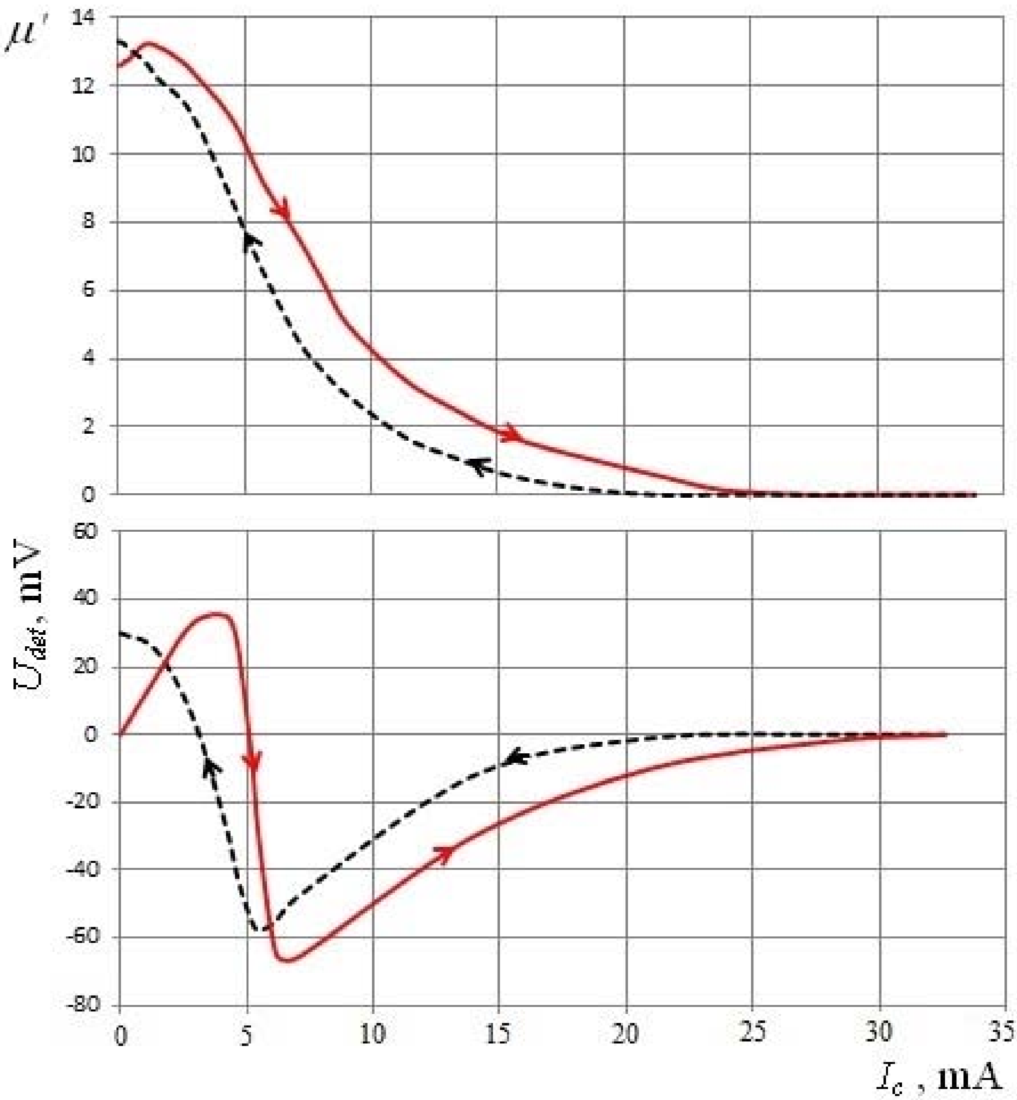

Fig.2. The dependence of differential magnetic permeability and the magnitude of the detected signal on bias current of magnetizing coil 5 (the solid lines – at increasing of the bias current, dash line - at decreasing of the bias current).

3. Discussion of the results and conclusions

Thus, the detection of amplitude-modulated microwave radiation in the ferromagnetic YIG at room temperature was experimentally obtained, which manifests itself as a change in the magnetic moment of a magnetized ferromagnetic sample under the influence of microwave magnetic field. The change in the magnetic moment of the sample was recorded by the magnetic sensor representing a horseshoe-shaped ferrite with an inductor. The measurement results show that the magnitude and sign of the detected signal depends significantly on the bias magnetic field H_0 and the shape of the magnetization curve.

As it was shown in [4], at the description of motion of the magnetic moment M in the variable magnetic field H, in the equation is necessary to consider the changing of the magnetic field in time (dH/dt):

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

(2)

where γ- gyromagnetic ratio, I – moment of inertia, **R** – dissipative term. Equation (2) indicates that the magnetic moment in addition to damped precession performs also an oscillating movement at the frequency of the alternating magnetic field.

At the microwave frequencies, these oscillations cannot be transferred to the region of registering inductor 5 (Fig. 1). However, the amplitude of oscillations of magnetic moment in the sample depends on the slope of the magnetization curve (on the differential magnetic permeability μ') at a given value of the bias magnetic field. Consequently, for the certain values of the bias magnetic field, the magnetic moment in the ferromagnetic sample will perform nonlinear oscillations.

In the region of the quadratic nonlinearity of magnetization curve, a low-frequency component of the magnetic moment in the ferromagnetic sample arises proportional to the amplitude of the microwave radiation. These low-frequency oscillations of magnetic moment in ferromagnetic sample can be transferred to the registering inductor via the horseshoe-ferrite and excite electromotive force in it (detected signal).

The analysis of the results of measurement shows that at the absence of the bias current through the magnetizing coil the detected signal equals zero (the solid lines in Fig. 2a and 2b). With the increase in the magnetizing current detected signal initially increases, reaching a maximum and then decreases to zero. Then the signal changes the polarity and starts to increase again until the next maximum (Fig. 2b). A further increase in magnetizing current causes saturation of the ferromagnetic sample, which in turn leads to a decrease of the detected signal. At full saturation signal is missing.

Comparison of the measurement results shows that the magnitude and sign of the detected signals correlate well with static curves of differential magnetic permeability. Particularly, the graphs in Fig. 2a and 2b show also that the residual magnetization retained in the system (see dash lines in Fig. 2a, b) when the magnetizing current is reduced to zero (due to the hysteresis of the magnetization curve). As a result, the detection is obtained even at the absence of an additional magnetizing bias field.

Thus, presented results can be successfully used for the detection and frequency conversion of electromagnetic radiation, as well as for recording, storing and processing of information, etc.

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