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Frequency Conversion in The Ferromagnet at Low Magnetic Bias Fields

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Abstract: The detection and second harmonic generation of microwave radiation in a ferromagnetic material at low magnetic bias fields was experimentally obtained at room temperature. On certain conditions, under the influence of the microwave signal, the magnetic moment of the magnetized ferrite performs nonlinear oscillations, which results the frequency conversion. The dependence of the converted signal on the magnetizing field was measured for different forms of the magnetization curve. It was shown that the conversion efficiency strongly depends on the shape of the magnetization curve of the ferromagnetic sample, as well as on the magnitude of the bias magnetic field. The results of this study may find applications for the registration and frequency conversion of radiation, for information data recording etc.

Keywords: Low magnetic bias field, nonlinear oscillations, ferromagnetic resonance, magnetic moment.

1. Introduction

The properties of ferromagnetic materials in the microwave fields were studied extensively at the beginning of the last century, after the experimental detection of ferromagnetic resonance.

The behavior of the magnetic moment in a magnetic field is described by the Landau-Lifshitz equation, which is significantly nonlinear. For the first time, the nonlinear phenomena in ferromagnetic materials in the microwave region were discovered by Bloembergen and Damon [1]. Later, numerous letters were published regarding the generation, detection, frequency conversion and amplification of microwave radiation using ferromagnetic materials (see for example [2, 3]).

These nonlinear phenomena occur only in the presence of a component of the microwave field perpendicular to the orientation of the constant magnetization of the ferromagnet. Phenomena occur at any amplitude of the microwave field, but, being a quadratic effect, they are clearly manifesting only at sufficiently large fields. Nevertheless, according to the Landau-Lifshitz equation, in the case of a parallel orientation of the alternating magnetic field with respect to the magnetic moment, no interaction between the microwave signal and the ferrite can occur.

However, there are many publications, where the changes of the magnetic moment of ferromagnetic sample was demonstrated under the influence of a linearly polarized electromagnetic radiation [4-8].

In [4] a mechanism is proposed to explain the nonlinear interaction of electromagnetic radiation with a magnetized ferromagnetic. 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 maximums), are in good agreement with the proposed mechanism of occurrence of non-linearity. However, it is generally considered that the abovementioned phenomena cannot be related to a magnetic nonlinearity of ferromagnetic, because in the optical region, magnetic permeability of ferromagnetic materials is practically equal to one. Therefore, the interpretation of the ultrafast magneto-optical response of ferromagnetic materials is still the subject of discussions.

In the present work, the detection and frequency doubling of the low-power microwave radiation in a magnetized ferromagnetic material is obtained, when the magnetic field of the microwave radiation is collinear to the magnetization vector of the ferromagnetic material. The dependence of the conversion efficiency on the parameters of the microwave signal and on the characteristics of the ferromagnetic sample was investigated.

2. Experimental setup and results of measurement

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

From the microwave generator 1 (VSG25A) modulated RF signal was fed to the primary coil wound around the investigated ferromagnetic sample 2 (see. Fig. 1). As a non-linear ferromagnetic sample, a low-frequency Nickel-Manganese ferrite with rectangular shape by dimensions of $2.8\times5.6\times8mm^3$ was used.

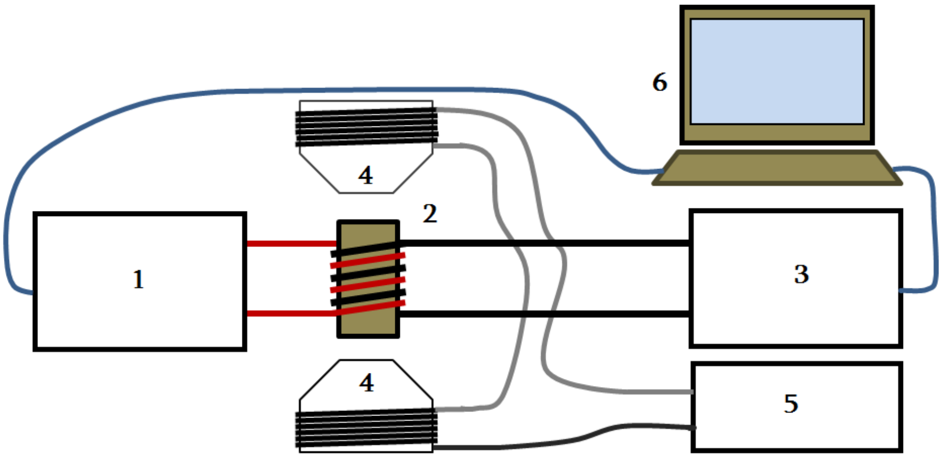

Fig. 1. The block diagram of experimental setup: 1-the microwave generator VSG25A, 2-low-frequency Nickel-Manganese ferrite, 3- USB-SA124B spectrum analyzer, 4-electromagnet, 5-controlled DC power supply, 6-PC

To obtain an effective transformation, it is necessary to magnetize the ferrite sample with a bias magnetic field, where the nonlinearity is maximal. For the magnetization of ferromagnetic sample, it was placed in a magnetic field of the controlled electromagnet 4.

In such configuration of the ferromagnetic sample and electromagnet, the magnetic field of microwave radiation proves to be parallel to the constant magnetizing field.

As was shown in [5, 6], one of the important characteristics of magnetic materials, which can be used for the estimations of nonlinear properties of materials, is the static magnetization curve. The magnetization curve can take various forms, depending on the composition, size and shape of the sample, as well as on the magnetic properties of the medium.

Therefore, we measured the static magnetization curve for the sample used in the experiments, which is completely described by the differential magnetic permeability of the sample:

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

The shape of the magnetization curve of our sample is shawn in Fig. 2a.

For registration of the detected signal (change in the average value of the magnetic moment of the sample under the influence of the microwave field, $\nu = \nu_{mod}$) and the signal at the double frequency ($\nu = 2\nu_0$), the secondary coil was also wound on the same ferrite sample, as shown in Fig. 1.

The signal on the secondary coil was detected by a USB-SA124B spectrum analyzer connected to a PC.

Measurements were made both in the sweep mode (sweep range is 0.5-2.5 GHz) and for a separate, fixed frequencies. It should be noted that the detection had non-resonant character and any features over the entire range of the microwave generator (0.5-2.5 GHz) were not obtained.

In Fig.2. along with the magnetization curve, the dependence of the magnitude of the detected signal (with the carrier frequency of the input microwave signal $\nu_0 = 1.5\,GHz$, and modulation frequency $\nu_{mod} = 120\,kHz$) on the bias magnetic field is shown (Fig. 2b). As expected, the maximal value of the detected signal is obtained when the bias magnetic field is $H \approx 50 Oe$; this is the region where the changes of slope of the magnetization curve of the ferromagnetic sample are most rapid. A similar dependence on the magnetic field bias was also obtained for the magnitude of the second harmonic.

Reversing the direction of the external magnetic field, leads to the reversal of the sign of the detected signal.

We measured the magnitudes of both the detected signal and the second harmonic of the signal, depending on the power of the main microwave signal ($\nu_0 = 1.5\,GHz$), results are pesented in Fig. 3.

The corresponding spectra of the signals (both the detected and the second harmonic), measured by the USB-SA124B spectrum analyzer, are presented in Fig. 4a and 4b, respectively.

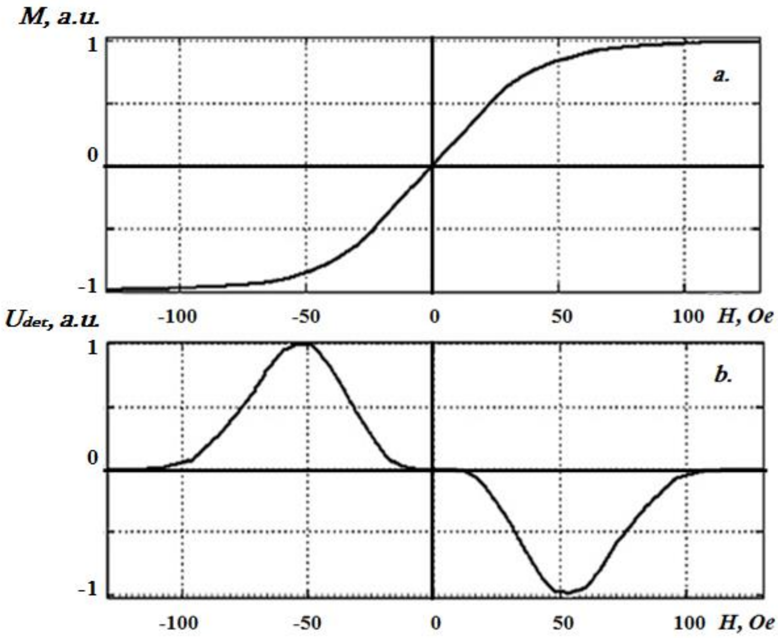

Fig. 2. a -The shape of the magnetization curve of Nickel-Manganese ferrite sample, b-The dependence of detected signal magnitude on bias magnetic field.

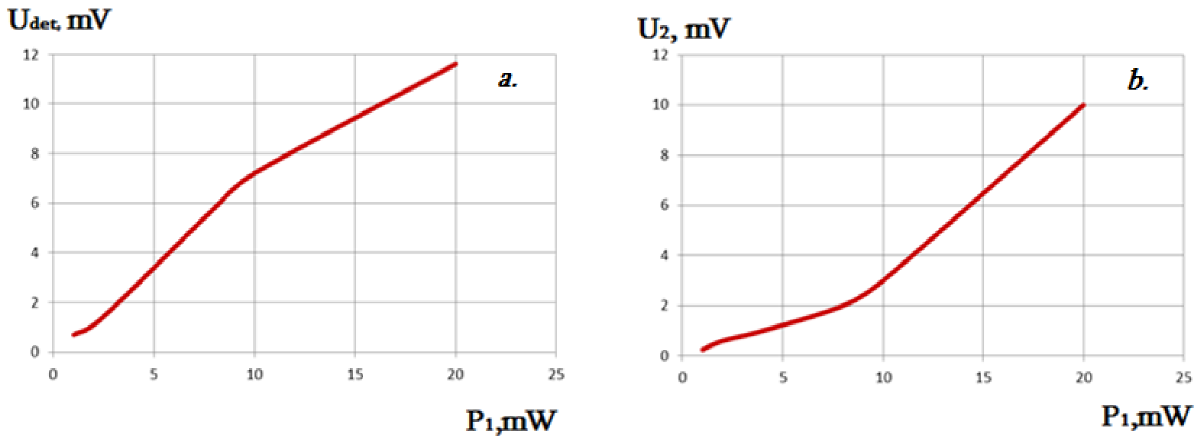

Fig. 3. The magnitudes of obtaind signals dependin on the power of the main microwave signal ($\boldsymbol{\nu}_0$=1.5 GHz, $\boldsymbol{\nu}_{mod}$ = 120 kHz): ***a***-detected signal ($\boldsymbol{\nu}_{det}$ = 120 kHz), ***b*** - second harmonic ($\boldsymbol{\nu}$=3GHz).

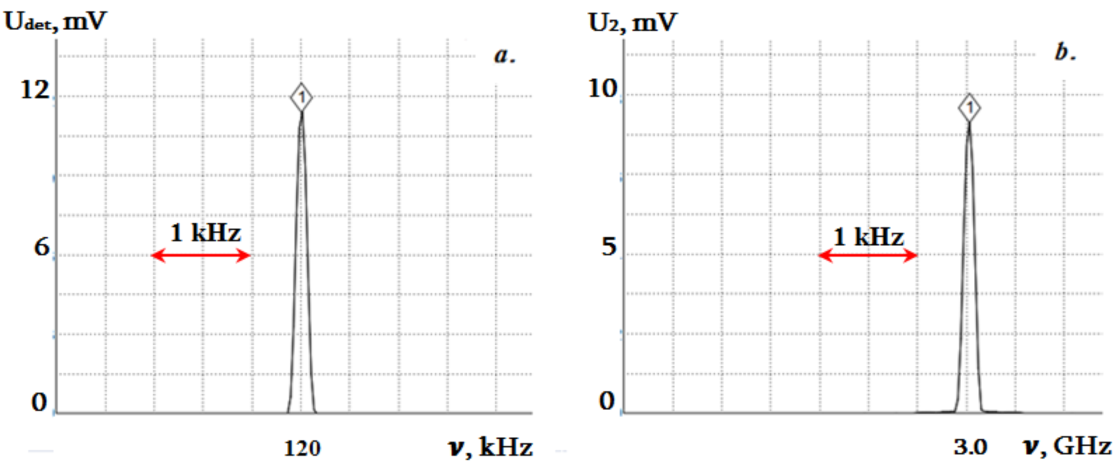

Fig. 3. ***a***-The spectrum of detected signal, ***b***-The spectrum of second harmonic signal.

3. Discussion and conclusions

Summarizing, the detection and frequency doubling of microwave radiation in the low-frequency ferrite at room temperature was experimentally obtained.

In [1-3] the nonlinear phenomena of ferrites are the result of a ferromagnetic resonance and manifest themselves only when the constant (magnetizing) $\boldsymbol{H_0}$ and alternating (microwave) $\boldsymbol{H_{\sim}}$ magnetic fields are mutually perpendicular.

However, our studies have shown that nonlinear interactions in the ferromagnet can also occur at the collinear arrangement of $\boldsymbol{H_0}$ and $\boldsymbol{H_{\sim}}$, which is impossible according to the Landau-Lifshitz equation. The measurement results show that the magnitudes of the detected signal as well as the signal on the doubled frequency significantly depends on the bias magnetic field $\boldsymbol{H_0}$ and the shape of the magnetization curve. This means that the magnetic moment, in addition to the damped precession, also oscillates at the frequency of the alternating magnetic field. 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, at 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 the magnetization curve, a low-frequency component, which is proportional to the power of the microwave signal, and the second harmonic of the microwave signal will appear in the spectrum of oscillations of the magnetic moment.

Comparison of the measurement results shows that the magnitude and sign of the detected signal, as well as the magnitude of the second harmonic signal correlate well with static curves of differential magnetic permeability.

In conclusion, we suppose that the results obtained can find practical applications in the detection and frequency conversion of electromagnetic radiation, in recording, information processing and storing etc.

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