New Method for Observation Ferromagnetic Resonance Spectra

I.V. Govorun[1], A.A. Leksikov[2]
[1]Krasnoyarsk scientific center SB RAS, Krasnoyarsk, Russian Federation
[2]L. V. Kirensky Institute of Physics, SB RAS, Krasnoyarsk, Russian Federation

Abstract **–A new method for observation of ferromagnetic resonance spectra is demonstrated. Its operation based on the registering a damping pole in the frequency response of two-resonator microstrip structure containing a sample under investigation. A damping pole arises due to mutual compensation of capacitive (electric) and inductive (magnetic) interactions between the resonators and this compensation get broken in the ferromagnetic resonance.**

Index Terms **– Microstrip resonator; coupling coefficient, ferromagnetic resonance; damping pole**

I. INTRODUCTION

ELECTROMAGNETIC properties of ferromagnetic thin films at microwave frequencies are important for understanding fundamental magnetic properties of these materials, as well as for potential applications of thin magnetic films in communication devices [1].

The method based on ferromagnetic resonance (FMR) is a common technique used to investigate fundamental properties of magnetic materials. This method allows measuring the main parameters of magnetic samples such as effective saturation magnetization, anisotropy, magnetostriction constants, easy or hard magnetization directions. In particular, FMR linewidth characterization has recently regained interest, due to that the resonance linewidth is related with damping of magnetization motion.

According to this method, a sample is exposed to a constant magnetic field and RF field simultaneously. A sample absorbs energy of microwave field at certain value of the frequency of this field. This frequency is the frequency of ferromagnetic resonance. Its value depends both on the external magnetic field and on a form and magnetic parameters of a sample.

The conventional FMR techniques are based on transmission line, for example coplanar waveguide [2]. Advantage of these techniques is a wide range of working frequencies. An ability of continuously frequency and external magnetic varying exists for these techniques. Drawback of these methods is their limited sensitivity.

Another ability for FMR observation in ferromagnetic samples is provided by resonator technique [3]. In this case sample is located in the antinode of magnetic microwave field of a resonator, for example microstrip or waveguide resonator. When the external field is swept there appears a change in the resonant frequency and the quality factor of the resonator. It should be noted, the strongest changes occur in conditions ferromagnetic resonance when the value of external magnetic field corresponds to the value of FMR field. The quality factor of resonator versus applied field matches to the dependence of image part of susceptibility on applied filed of the tested sample. The resonant frequency versus external magnetic field matches to the dependence of real part of susceptibility on applied filed of the sample.

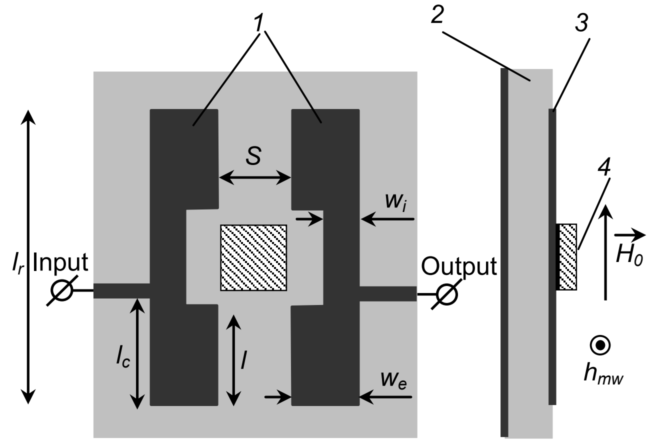

Fig. 1. Design of the FMR sensor.

Today, there is an active interest in observation of resonance in thin magnetic films of hundred nm thick. Continuous miniaturization of microwave devices based on thin magnetic films (TMF) and also increasing in density of magnetic memory lead to significant reduction of the sizes of samples used. Besides, verification of micromagnetic modeling can be realized only for TMF samples of micron size.

Today conventional resonant techniques cannot provide sensitivity being enough to measure FMR in TMF samples of micron dimensions. When the dimensions of TMF sample are decreased, the filling factor of the resonator influencing the level of FMR signal decreases, too. The anticipated FMR signals from small-size TMF to be weak compared with background noise.

At present there exist methods of observation FMR spectra in magnetic films of micrometer size [4, 5]. Application of planar microresonator to investigate an angular magnetic response of single magnetic nanostructure is described in [4]. The eigenfrequency of this resonator is 14.23 GHz with a quality factor equal to 14. The proposed microresonator is able to measure high frequency dynamics of single magnetic sample with dimensions 5×1×0.02 µm. Very high sensitivity of this device is due to a great value of filling factor. Also the

978-1-5386-7054-5/18/$31.00 ©2018 IEEE

on-chip microwave interferometer is presented in [5]. The device automatically cancels the background parasitic noise. A FMR and damping property of a single 240 nm wide Permalloy nanowire were measured. But each of these methods requires a very precise and accurate fabrication.

II. Problem Definition

Therefore the actual and important task is developing and designing of operative, simple and precise method for measuring parameters of small-size TMF.

In this paper a new method for observing FMR spectra in small size TMF is proposed. The sensor based on this method is simple for fabrication and provides adequate accuracy of measurement the main TMF parameters.

III. Theory

As is known [6], resonators interact with each other through the electromagnetic field. This interaction is described by the total coupling coefficient $k(f)$, which is algebras sum of capacitive and inductive coupling coefficients:

$$k(f) = \frac{k_L(f) - k_C(f)}{1 - k_L(f)k_C(f)} \qquad (1)$$

where $k_L(f)$ and $k_C(f)$ are inductive and capacitive coupling coefficients reflecting interactions through magnetic and electric fields, respectively. They describe electric and magnetic interactions between resonators and are expressed through the energies, stored by resonators separately and jointly. These energies are determined by distribution of microwave currents and voltage along the resonator's length. On frequency response of a pair microstrip resonators a deep minimum of transmission, the so called damping pole, may exist. At this frequency no coupling exists between the resonators and almost all power is reflected from the input of this device. It means, that the total coupling coefficient equals zero at the damping pole frequency. Note, the damping pole is the point of mutual compensation of capacitive and inductive coupling coefficients.

If one of the interactions is changed, frequency of mutual compensation will shift. So the damping pole frequency will change too.

If a sample of thin magnetic film is located between resonators in an area of maximum of magnetic interaction the inductive coupling changes, because sample has a magnetic permeability unequal to 1. So moreover in FMR conditions magnetic MW permeability reaches maximum value. Changes in magnetic coupling caused by changing a magnetic MW permeability lead to a shift the frequency location of damping pole. So, when an external magnetic field is swept damping pole frequency reflects a behavior of a magnetic MW permeability of sample in FMR conditions. This is a key issue in the proposed technique.

Thus, to observe the FMR spectra of ferromagnetic samples, registration of frequency and attenuation level of the damping pole of a sensor should be performed.

The proposed FMR sensor (Fig.1) is a structure consisting of two microstrip resonators. The antinodes of microwave current at resonant frequency are located in the central parts of such half-wave resonators where a sample of thin magnetic film is placed (see *4* Fig. 1). For such construction the dependence of total coupling coefficient |k| versus the distance between conductors of resonators has an anomalous dependence at the first mode frequency of the resonators (Fig. 2).

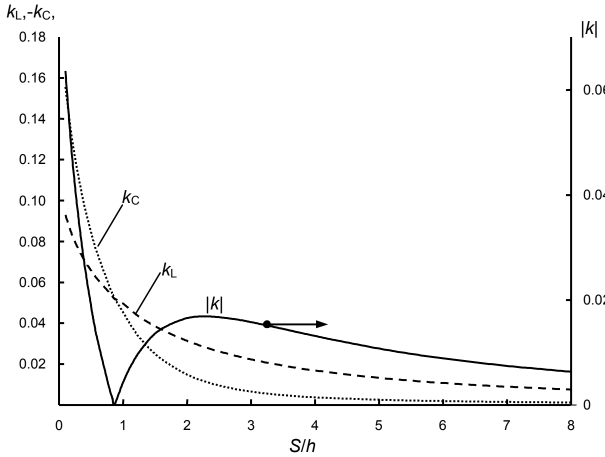

Fig. 2. Dependences of the coupling coefficients of the two-section structure on the gap between the resonators normalized by the substrate thickness at frequencies of the first passband. The solid curve is modulus of the total coupling coefficient, the dotted curve is capacitive coupling coefficient, the dashed curve is inductive coupling coefficient [7].

Figure 2 shows plots of the modulus of the total coupling coefficient |*k*| and the coefficients of inductive (k_L) and capacitive (k_C) coupling between microstrip resonators (Fig. 1) versus the distance *S* between their conductors normalized to the substrate thickness *h* [7].

It is seen from Fig. 2, total coupling coefficient initially decreases with increasing the distance *S* and sharply drops to zero at a certain gap. Then it reaches a maximum value. On further increasing the distance between the resonators the total coupling coefficient behaves a normal monotonic decreasing.

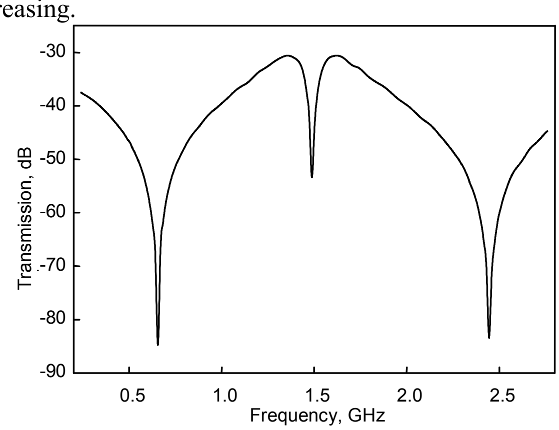

Fig. 3. Frequency response of the fabricated FMR sensor in a range of first passband

The situation is interesting when the total coupling coefficient becomes zero at certain value of spacing between the resonators. In this point the total coupling coefficient becomes zero, moduli of the coefficients k_C and k_L are equal each other and their signs are opposite. At this value of gap between resonators the damping pole appears at frequencies of the first passband and destroys it (Fig. 3). In this case, a high level reflection of microwave power from the input of the microstrip structure is observed. On the base of this phenomenon the reflective power limiter had been created earlier [8].

In a case when coefficient $|k|$ is equal to zero at the first passband frequency, the two-section construction (Fig. 1) possesses a very high sensitivity to a weak changing of magnetic coupling between resonators. Thus this device can be used for observing FMR spectra in a sample of TMF with a small size. It should be noted, that sensor based on this technique is enough easy in designing and its fabrication do not demand a very precision technology.

IV. Experimental Results

In Fig. 1 the strip conductors topology of the sensor is shown. The considered sensor consists of two microstrip stepped-impedance resonators *1* on substrate *2*, the bottom surface *3* of which is completely metal-coated.

The device was simulated using program Sonnet Lite. The topology of the conductors shown in Fig. 1 and the prototype of sensor was manufactured on the alumina substrate with thickness of 0.5 mm (ε = 10.6). The lengths of all the three parts of resonators were 12.5 mm, their widths being equal to 3 mm and 1.1 mm. The spacing between the wide parts of resonators was 0.65 mm.

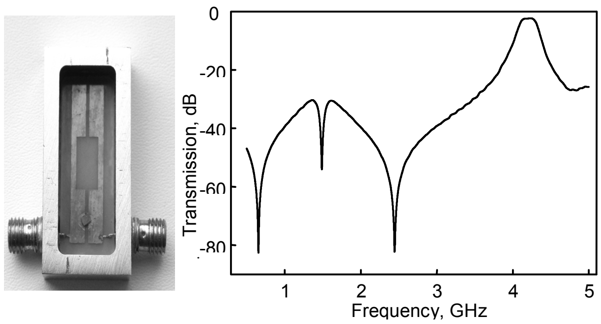

Fig. 4. Photograph of the sensor prototype without the test sample and its frequency responses measured in a range of the first and second passband.

Substrate with a size 10.7 mm×30 mm is mounted in a nonmagnetic (brass) case and distance between the substrate and upper wall is equal 7 mm (Fig. 4).

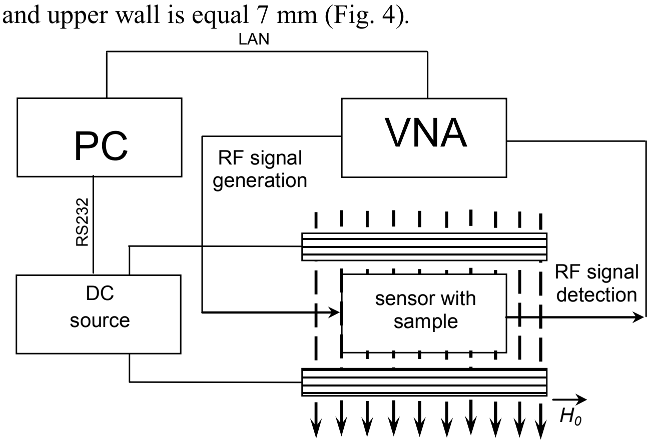

Fig. 5.Experimental setup block diagram.

It can be seen (Fig. 3) the damping pole appears at frequencies of the first passband, whose frequency is equal to 1.492 GHz. Transmission coefficient at the frequency of damping pole is equal to 54.5 dB. However there is a second passband with central frequency 4.2 GHz (Fig. 4).

The thin magnetic film of Permalloy $Ni_{75}Fe_{25}$ was used as a test sample. It was produced by vacuum deposition on 0.5 mm glass substrate whose size was 3 mm × 3 mm. The thickness of produced sample was 500 nm.

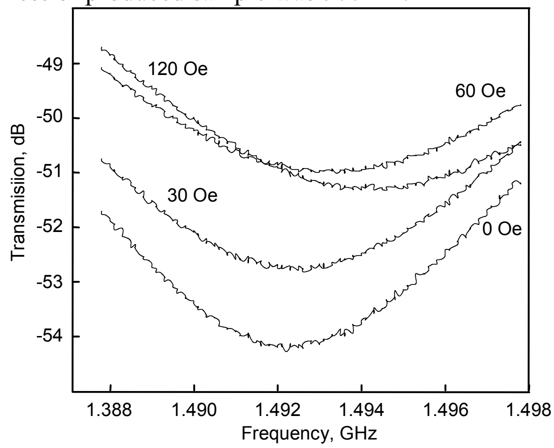

Fig. 6. S_{21} changes versus different fields for the situation when direct magnetic field is applied along easy axis of the sample.

The block diagram of the experiment setup is shown in Fig. 5. A microwave signal from a vector network analyzer (VNA) was introduced through the input port. It generates a microwave magnetic field h_{mw}, located in the plane of the sample. Pair of Helmholtz coils is used to supply magnetic fields up to 120 Oe along to the microstrip resonators. The static magnetic field H_{dc} was applied in the plane of the film, perpendicular to the microwave field h_{mw} and parallel to the easy axis or to the hard axis of the sample.

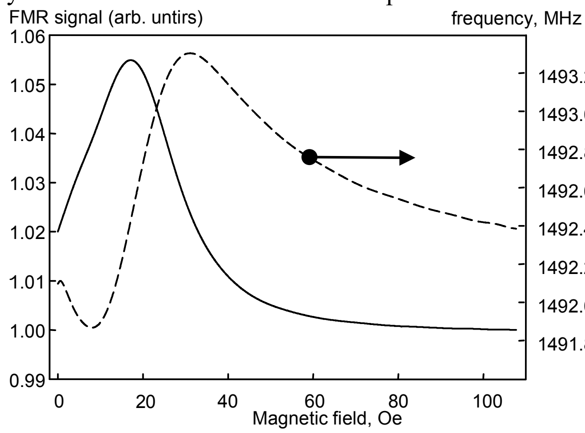

Fig. 7. Solid curves are normalized transmission coefficient at the damping pole frequency as function of applied external magnetic field and the dashed curves are the sensor damping pole frequency as function of applied external magnetic field.

In Fig.3 and Fig.4 the frequency dependence of the transmission coefficient of the developed prototype of the sensor is demonstrated. The results were obtained with VNA Rohde&Schwarz ZVL 13.

The frequency responses of the sensor were measured in the dc magnetic field ranging from 120 Oe to 0 Oe.) .The data are presented in Fig. 6.

Fig. 7 represents normalized transmission coefficient at the damping pole frequency (solid curves) and the damping pole frequency of the sensor (dashed curves) as function of applied magnetic field strength.

V. DISCUSSION OF RESULTS

The setup (Fig. 5) was then used to obtain the standard microwave S_{21} parameters of the sensor with the sample as a function of external magnetic field H_0. There is a shift of frequency of damping pole when the static magnetic field changes its value (Fig. 6).

The normalized transmission coefficient at the damping pole frequency versus applied field is similar to the image part of susceptibility of the tested sample (Fig. 6 solid curve). The damping pole frequency versus external magnetic field is similar to the real part of susceptibility of the sample (Fig. 6 dashed curve). A resonance field H_{res} of 8.34 Oe and 13.7 Oe and linewidth value ΔH of 13.7 Oe and 16.6 Oe for easy axis and hard axis, respectively, were obtained from these data.

Parameters of the sample measured by suggested sensor are in agreement with the parameters obtained with help of local spectrometer of FMR [3].

VI. CONCLUSION

A FMR sensor having a structure of two-pole microstrip section is presented. The device consists of two microstrip half-wave stepped-impedance resonators. Principle of operation of the sensor is based on the registration of a damping pole in its frequency response. Sensor operability is demonstrated by measurements of Permalloy thin film parameters at a frequency of 1.492 GHz.

It is concluded that the proposed technique based on the recording frequency and attenuation level of the damping pole is suitable for observation FMR in a sample of thin magnetic film. The method allows simplify FMR measurements in a sample of thin magnetic film.

REFERENCES

[1] B.A. Belyaev, K.V. Lemberg, A.M. Serzhantov, A.A. Leksikov, Ya. F. Bal'va, An.A. Leksikov, “Magnetically tunable resonant phass shifters for UNF band,” // IEEE Transaction on Magnetics. vol. 51, 6949649, June 2015.

[2] S.S. Kalarickal, P. Krivosik, M. Wu, C.E. Pratton, M.L. Schneider, P. Kabos, “Ferromagnetic resonance linewidth in metallic thin films: comparison of measurement methods,” // Journal of Applied Physics. vol. 99, 093909, 2006.

[3] B.A. Belyaev, A.V. Izotov, A.A Leksikov, “Magnetic Imaging in Thin Magnetic Films by Local Spectrometer of Ferromagnetic Resonance,” IEEE Sensors Journal, vol. 5, pp. 260–267, 2005.

[4] C.Schoeppner, K. Wagner, S. Stienen, R. Meckenstock, M. Farle, R. Narkovwicz, “Angular dependent ferromagnetic resonance analysis in a single micron sized cobalt stripe,” // Journal of Applied Physics. vol. 116, 033913, 2014.

[5] H. Zhang, R. Divan, P. Wang, “Ferromagnetic resonance of a single magnetic nanowire measured with an on-chip microwave interferometer,” // Review of Scientific Instruments. vol. 82, 054704, 2011.

[6] V.V. Tuyrnev, “Coupling coefficients of resonators in microwave filter theory,” // Progress in. Electromagnetic Research B. vol. 21, pp. 47-67, 2010.

[7] I.V. Govorun, A.A. Leksikov, A.M. Serzhantov. “Features of the coupling coefficients of microstrip irregular quarter-wavelength resonators” // 13th International Scientific-Technical Conference Actual Problems of Electronics Instrument Engineering (APEIE) vol. 04, pp. 29-32, 2016.

[8] B.A. Belyaev, I.V. Govorun, A.A. Leksikov, A.M. Serzhantov, An.A. Leksikov, “Reflective power limiter for X-band with HTSC Switching element,” // IEEE Transactions on applied superconductivity. vol. 26, 7407639, September 2016.

Govorun Ilya Valerievich, Candidate of Engineering Sciences, researcher department of molecular electronics, scientific center SB RAS Krasnoyarsk. The area of scientific interests is development and investigation stripe microwave devises on base of substrates with high dielectric permeability, coupling coefficient, HTSC. Author and co-author of more than 24 scientific works and 2 patents for invention.

Leksikov Aleksander Aleksandrovih, Doctor of Engineering Sciences, leading researcher of electrodynamics and microwave electronics laboratory of Kirensky Institute of Physics, Krasnoyarsk, professor of Siberian Federal University and Siberian State Aerospace University. The area of scientific interests is electrodynamics of wave-guiding structures on substrate with high dielectric constant and developing microwave electronics device on its base, physics of magnetic phenomena and optics. Author and coauthor of more than 83 scientific and educational methodical works and 40 patents for inventions.