ISSN 1063-7850, Technical Physics Letters, 2015, Vol. 41, No. 4, pp. 324–327. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © A.N. Babitskii, B.A. Belyaev, G.V. Skomorokhov, A.V. Izotov, R.G. Galeev, 2015, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2015, Vol. 41, No. 7, pp. 36–44.

A Weak-Field Magnetometer Based on a Resonator Microstrip Transducer with Thin Magnetic Films

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Received July 15, 2014

Abstract—A high-sensitivity magnetometer of weak quasi-stationary magnetic fields is developed and investigated. The magnetometer transducer is a microstrip resonator with an active medium from thin magnetic films prepared by magnetron sputtering of a $Ni_{75}Fe_{25}$ permalloy target. It is demonstrated that the transducer exhibits the maximum sensitivity not only in the optimal dc magnetic field, but also at the optimal deviation of this field from the rf pump field polarization direction. The magnetometer operates in a wide dynamic range of measured magnetic fields from 10^{-4} to 10^{-2} μT at frequencies of 10^{-1}–10^{5} Hz.

DOI: 10.1134/S1063785015040021

High-sensitivity weak-magnetic-field magnetometers are used in solving a variety of research and engineering problems, including, first of all, problems of geomagnetometry in studying the geological structure of the Earth and exploratory work [1]. In addition, these magnetometers are used in burglar alarm systems, medicine, and special equipment [2]. It is well-known that the lowest threshold sensitivity ($\sim 10^{-15}$ T) is characteristic of SQUID magnetometers [2]; however, these are complex, expensive, power-consuming, and bulky devices. In SQUID magnetometers, cryogenic temperatures are ensured using liquid helium; therefore, they are difficult to apply under field conditions. There exist different high-sensitivity quantum magnetometry techniques that are promising for application in magnetic-field strength metrology [3]; however, devices based on them can be successfully used only in solving special problems. Easy-to-operate ferroprobe magnetometers [4] have been widely used despite the much lower threshold sensitivity ($\sim 10^{-10}$ T). It should be noted that the upper boundary of the ferroprobe operating frequency band is only few kilohertz, while some applications, e.g., pulsed electrical exploration with artificial excitation of a medium, require a magnetometer operating frequency band of tens of kilohertz [5]. Therefore, the development and study of the high-sensitivity broadband magnetometers is an important problem.

The narrow operating frequency band of both the ferroprobe magnetometers and magnetometers based on thin magnetic films (TMFs) [5–7] is determined by inductive magnetic field sensors used in them. In such sensors, rf pumping and signal pick-off are performed using coils winded directly on a soft magnetic core or on a TMF substrate. Obviously, the coil blocks shield external rf magnetic fields and, thus, significantly decrease the upper boundary of the magnetometer operating frequency band. Microstrip thin-film sensors are free from these drawbacks and much more readily manufacturable [8–10].

This Letter proposes a magnetic-field sensor (Fig. 1a) in the form of an irregular quarter-wavelength microstrip resonator (MSR) with a strip conductor consisting of two regular segments. A broad strip conductor is formed on a high-permittivity substrate and has one free end, with the other end connected with a short-circuited narrow conductor. A magnetic film sputtered on its own substrate is located under the narrow conductor in an antinode of microwave magnetic field *h*. The sensor has two ports with capacitive coupling for matching. One port is connected with a microwave pump, while the useful signal is output from the other port. The highest performance is shown by sensors in which multilayer magnetic structures possessing uniaxial anisotropy. These structures consist of metallic magnetic films prepared by means of sputtering with a thickness compared to the skin layer and divided by dielectric layers that exclude ohmic contact between the films in order to decrease eddy currents.

The active medium of the investigated sensor is magnetic film structures consisting of two 150-nm-

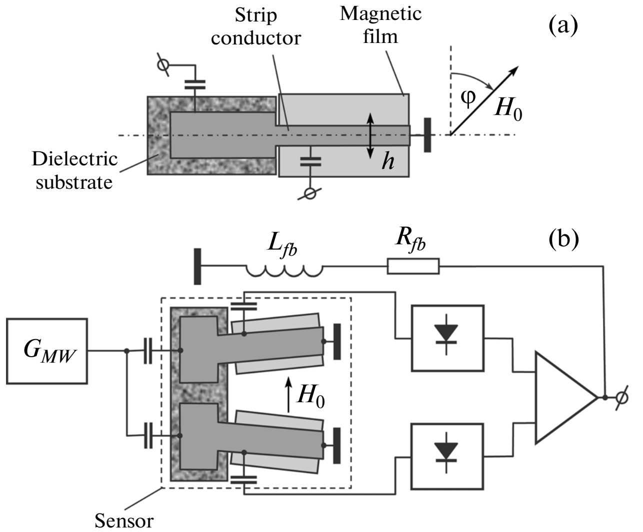

Fig. 1. (a) Microstrip resonator with a thin magnetic film and (b) block diagram of the magnetometer.

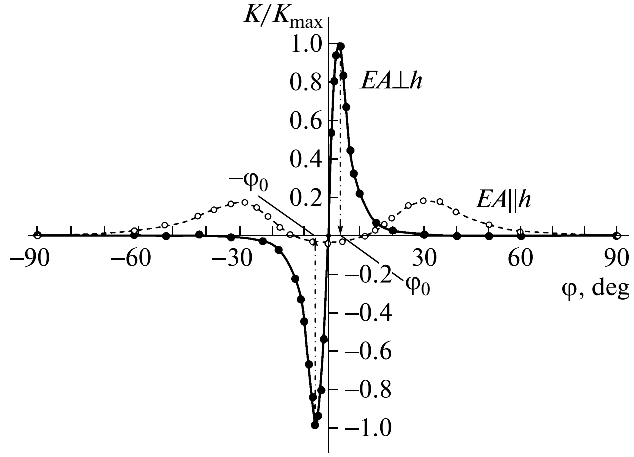

Fig. 2. Dependences of the transformation coefficient of the microstrip resonator transducer on the angle of the bias magnetic field direction for two orientations of the easy magnetization axes relative to the rf field polarization.

thick permalloy layers separated by a 500-nm silicon monoxide spacer. The magnetic films were prepared by magnetron sputtering of a $Ni_{75}Fe_{25}$ target onto ST-50 glassceramic substrates with a standard size of 60 × 48 mm preliminarily coated by a 500-nm-thick layer of silicon monoxide. Uniaxial magnetic anisotropy H_k was induced by a uniform dc magnetic field applied in the substrate plane during sputtering. As a result, the easy magnetization axis (EMA) formed in the film structure plane was parallel to the magnetic field applied during TMF sputtering. In zero magnetic field, the film magnetic moments after deposition are aligned along this axis.

The sensor under study was biased by in-plane magnetic field H_0 oriented at angle φ to the polarization direction of rf magnetic field h (Fig. 1a). Our investigations showed that transformation coefficient K, i.e., the ratio between the useful signal at the sensor output and the measured magnetic field, depends on both the value and direction of the bias magnetic field. Figure 2 shows the dependences $K(\varphi)/K_{max}$ built at the orthogonal (closed circles) and parallel (open circles) EMA orientations in the TMFs. It can be seen that at the orthogonal EMA orientation, the transformation coefficient is maximum at $\varphi_0 \approx 5°$. This maximum exceeds the other maxima observed at $\varphi \approx \pm 30°$ at the parallel orientation by a factor of almost five. Note that the maximum transformation coefficient of the sensor is attained at the dc magnetic field $H_0 = H_k$, but the field stronger than the anisotropy field ($H_0 \approx 1.3H_k$) was used. Such a bias makes it possible to significantly reduce magnetic noise in the TMFs, which, as is known, has a pronounced maximum in the magnetic field $H_0 = H_k$.

It should be noted that at, $\varphi_0 \approx -5°$, the transformation coefficient has the minimum value that amounts to the maximum value with the negative sign. Therefore, the use of two microstrip sensors in the magnetometer sensitive element, in which the narrow strip conductors are formed at angles $\pm\varphi$ to the resonator axes (Fig. 1b), allows doubling the useful signal after summation on an operational amplifier. In this case, the magnetometer contains pump G_{MW}, which feeds the sensitive element consisting of two MSR sensors. Signals from the MSR are supplied to amplitude detectors and, then, to the operational amplifier, which sums and amplify them. In such a structure, at the microwave pump frequency coinciding with the resonant MSR frequencies, the pump amplitude noise is significantly compensated, since the sensor voltages after detectors are subtracted on the operational amplifier. Obviously, the TMF magnetic noise level in such a circuit also decreases, but only by a factor of $\sqrt{2}$. Long-time stability of transformation coefficient K is ensured using the compensation method. For this purpose, the sensitive element is placed in feedback coil L_{fb} (Fig. 1b), which compensates with high accuracy the measured field value by its magnetic field. As a result, the stability of coefficient K is mainly determined by the stabilities of the coil constant and feedback resistor R_{fb} [1], which load the operation amplifier (Fig. 1b). The compensation coil is made of Helmholtz coils, which significantly reduce shielding of rf magnetic fields and, thus, broaden the operating frequency range of the magnetometer. Note that inductance L_{fb} also determines the upper pass band frequency, when the coil reactive resistance becomes unacceptably high. However, the reduction of inductance L_{fb} for further broadening of the operating frequency range will require a corresponding increase in the compensation circuit power.

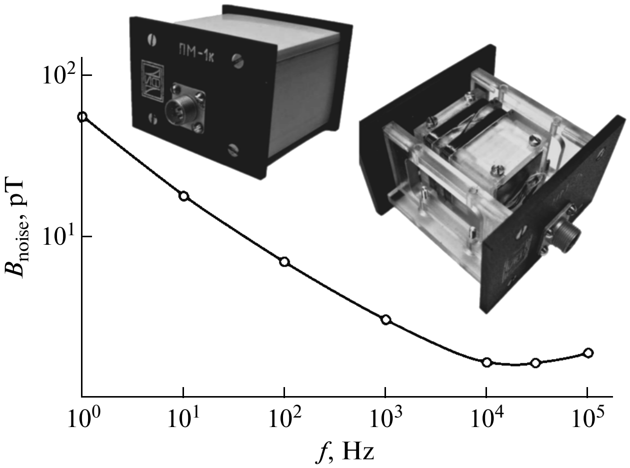

Fig. 3. Frequency dependence of the noise amplitude measured in a band of 1 Hz and photographs of the magnetometer with and without a protective case.

As is known, the main magnetic parameters of the TMFs, which determine the characteristics of microwave sensors, are magnetic susceptibility dependent on saturation magnetization M_s, anisotropy field H_k, and ferromagnetic resonance (FMR) linewidth ΔH, as well as amplitude and angular dispersions δH_k and $\delta\alpha_k$ of the uniaxial anisotropy that determine the magnetic noise. The sensors are traditionally based on permalloy films with the composition $Ni_{80}Fe_{20}$ close to the composition with zero magnetostriction. These films have the following parameters: the FMR linewidth measured at a frequency of 2.3 GHz is $\Delta H \approx 7$ Oe, the anisotropy is $H_k \approx 5$ Oe, and the saturation magnetization is $M_s \approx 860$ G. Parameters δH_k and $\delta\alpha_k$ of these TMFs are small, which significantly reduces the magnetic noise. Chemically deposited cobalt films [11] exhibit high magnetic susceptibility in the microwave range and are promising for application in magnetic sensors; however, the problem of aging of these films remains unsolved.

The $Ni_{75}Fe_{25}$ permalloy films fabricated by us exhibit the saturation magnetization $M_s \approx 1100$ Gs, the magnetic anisotropy $H_k \approx 8$ Oe, and the FMR linewidth at a frequency of 2.3 GHz $\Delta H \approx 5$ Oe, which are much better than the characteristics of the $Ni_{80}Fe_{20}$ films. The significant reduction of the film noise in the investigated sensor has two causes. First, the longer TMF edges, which are the main noise source, do not fall into the MSR rf magnetic field region (Fig. 1a) and do not participate in signal formation. Second, the film size is small (10 × 5 mm) due to the small microwave sensor size (15 × 5 mm); consequently, the values δH_k and $\delta\alpha_k$ are small as well [11]. The distributions of M_s, H_k, EMA direction, and FMR linewidth were measured using a scanning FMR spectrometer [12] over the entire area of the fabricated TMF structure (60 × 48 mm^2). This allowed us to cut out magnetic structure parts of specified sizes with the most homogeneous characteristics and, thus, minimize the TMF noise. It was established that the noise of the designed magnetometer is low and caused mainly by the circuit elements, including the pump, detectors, and operational amplifier. The chosen pump frequency was rather low (~0.5 GHz) to ensure a sensor operation regime close to the FMR in relatively weak bias fields H_0.

One of the most important characteristics of magnetometers is the threshold measured field sensitivity, which is characterized by noise amplitude B_{noise} measured, as a rule, in the frequency band with a width of 1 Hz. Figure 3 shows the experimental dependence of B_{noise} on measured signal frequency f for the fabricated magnetometer. The noise was measured under laboratory conditions. The magnetometer was placed inside a trilayer permalloy magnetic shield with a wall thickness of 1.0 mm and fed by accumulators. The output signal was measured with a selective nanovoltmeter. It can be seen that the noise amplitude is rather small. As the frequency is increased, it first drops and then starts growing. The minimum of the dependence $B_{noise}(f)$ lies within 10^4–10^5 Hz.

Figure 3 shows a photograph of the fabricated magnetometer with and without a protective case. The board of the microwave generator based on a BF998 insulated-gate field-effect transistor and an output amplifier based on a MAX9943 chip are located in two separate compartments of brass cases to ensure high-quality shielding. The sensitive element with two TMF MSRs, detectors, and an original magnetic system for inducing bias field H_0 are located on a special platform at the center of the compensation Helmholtz coils. The magnetic system inducing bias $H_0 \approx 10$ Oe is based on miniature dc magnets and magnetic conductors made of soft magnetic iron.

The developed and fabricated weak-magnetic-field magnetometer prototype has the following technical characteristics: the measured magnetic field range is 10^{-4}–10^2 μT, the operating frequency range is 10^{-1}–10^5 Hz, the transformation coefficient is 60 mV/μT, the supply voltage is ±9 V, the working power is 0.24 W, the dimensions are 66 × 61 × 46 mm, and the weight is 140 g.

Thus, we developed an original magnetometer based on microstrip resonator structures with thin magnetic films, which is simple, manufacturable, and has a broader operating frequency range and higher threshold sensitivity than do the available magnetometer designs. The magnetometer can be used in studying the geological structure of the Earth and in exploratory work, including pulsed electrical exploration with artificial excitation of a medium. The miniature size and small weight of the magnetometer make it possible to mount it on light unmanned aerial vehicles.

It should be noted that the magnetometer has a figure-eight directional pattern similar to the patterns of other magnetometers, e.g., ferroprobe or magnetic-film-based ones. Therefore, three identical magnetometers with the orthogonal maximum sensitivity directions can measure not only the value, but also the direction, of a magnetic field. The developed magnetometer allows significant broadening of the operating frequency band. For this purpose, it is necessary to enhance the microwave pump frequency and reduce the Helmholtz coil inductance in the feedback circuit.

Acknowledgments. This study was supported by the Ministry of Education and Science of the Russian Federation, state order for Siberian Federal University in 2014, task no. 3.528.2014K.

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Translated by E. Bondareva