Low Noise Wideband Thin-Film Magnetometer

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***Abstract*—A novel low noise and wide bandwidth thin magnetic film magnetometer based on a ferromagnetic resonance phenomenon is presented in the article. The magnetometer is characterized by a high sensitivity in a wide frequency range - from a direct component of the field and up to 10^5...10^8 Hz. The magnetometer noise level is lower 10^{-12} T/Hz$^{1/2}$ at frequencies above 10^2 Hz. The magnetometer conversion factor is constant at the whole operating frequency band. The developed magnetometer is simple and inexpensive for mass production.**

Keywords—magnetic sensor; magnetometer; magnetic field measurement; thin magnetic film

I. INTRODUCTION

High-sensitivity weak-magnetic-field magnetometers are used for solving a variety of research and engineering problems, including, e.g., problems of geomagnetometry in studying the geological structure of the Earth and exploratory work [1]. It is well known that the lowest threshold sensitivity (~10^{-15} T) is characteristic of superconducting quantum interference device (SQUID) and quantum magnetometers; however, these are complex, expensive, power-consuming, and bulky devices [1]. Easy-to-operate fluxgate magnetometers are widely used despite the much lower threshold sensitivity (~10^{-11} T). It should be noted that the upper boundary of the fluxgate 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.

Despite of the thin magnetic film (TMF) magnetometers are well-known magnetometer type [2], we recently proposed a new TMF-magnetometer type [3, 4] based on the ferromagnetic resonance phenomenon (FMR). Fig. 1 shows main types of magnetometers and some of their characteristics (sensitivity, measuring range, bandwidth) in order to compare them with developed TMF-magnetometer characteristics described in the article. As can be seen from the figure, the TMF-sensors have a wide frequency bandwidth and a high sensitivity at the same time. For example, the magnetometer noise level at the frequency 10^2 Hz is lower than 10^{-12} T making possible to use it as a compact high sensitivity magnetometer for measuring an alternating magnetic field parameters. On the other hand, the TMF-magnetometer is suitable for measuring of stationary magnetic field parameters. The magnetometer characteristics are comparable to those of flux-gate magnetometers at low frequencies. At frequencies above 10^4 Hz it may be appropriate to use coil-sensors because their sensitivity increases with frequency and may be higher than that of SQUID. However, TMF-magnetometers distinctive feature is a wide bandwidth measuring capability - from 0 Hz to 10^8 Hz with a constant conversion factor. That is important for pulse measurements (e.g. in geomagnetic for pulse measurements during artificial medium excitation).

II. THE SENSOR PRINCIPLE OF OPERATION

Fig. 2 shows the TMF-magnetometer block diagram. A TMF with uniaxial magnetic anisotropy is excited by in-plane AC magnetic field H_{RF} along the hard axis (HA) of magnetization. Additionally in the film plane a constant bias field H_{bias} is applied at a small angle α ~ 5-10° to the HA. In this case, the maximum sensitivity of the magnetometer approximately coincides with the easy axis (EA) of magnetization. The magnetometer uses a magnetic compensation system to improve long time stability of a conversion factor. The compensation field is applied along the EA. In several cases, the magnetometer includes a modulation field forming system. This field is co-directed to the maximum sensitivity direction, i.e. it is applied along the EA.

The magnetometer sensitive element is a thin magnetic film prepared by vacuum deposition of a nonmagnetostrictive permalloy $Ni_{80}Fe_{20}$ (saturation magnetization $M_s \approx 860$ G, the uniaxial magnetic anisotropy field $H_a \approx 5$ Oe) on a ceramic substrate. Uniaxial magnetic anisotropy of the thin film was induced by a uniform magnetic field applied in the substrate plane during deposition. Generally, the TMF-magnetometer conversion factor is proportional to the magnetic film volume. Therefore, the more TMF-layers, the higher the sensor sensitivity is. However, the number of film layers does not usually exceed five because of the skin effect. The total film thickness is usually less than 10^4 Å.

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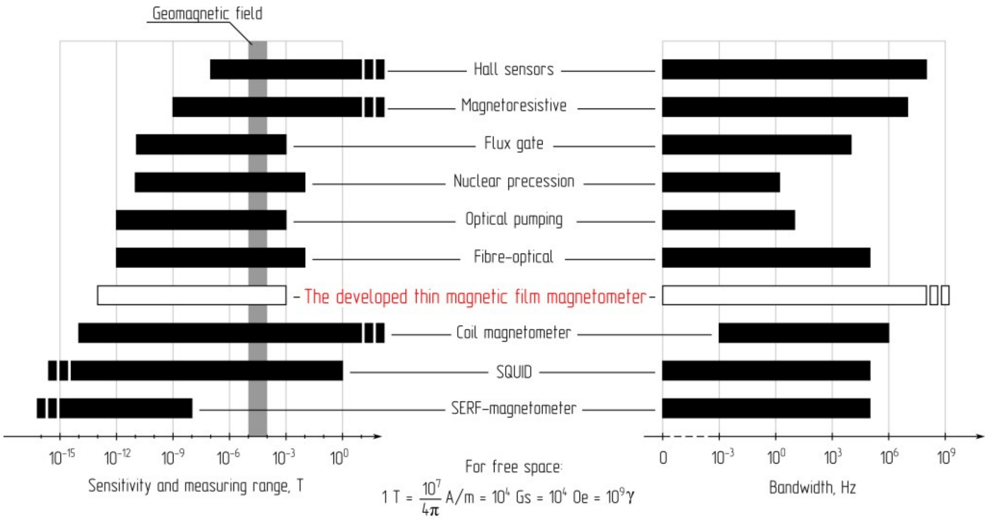


Fig. 1. Magnetometers classification and the place of the developed TMF-magnetometer

The thin magnetic film is placed in the inductive part of the microstrip resonator that produces the high frequency excitation magnetic field H_{RF} along the HA. It is important to place TMF in the maximum current flow location, i.e. in the maximum H_{RF} amplitude region. To form H_{RF} multiturn coil can be used but that decreases resonance frequency and as a result requires reducing of the film size. The optimum excitation frequency depends on film material properties. It is about 600-800 MHz for permalloy $Ni_{80}Fe_{20}$.

The constant biasing magnetic field H_{bias} is applied at the angle α to the HA. Helmholtz coils can also form the biasing field but it is usually created by a permanent magnets system. The bias magnets are placed in a mechanical system that allows adjusting the angle α between the H_{bias} direction and the HA. It is possible to realize various modulation modes by modulating of the biasing field H_{bias}. The measuring magnetic field H_{meas} is directed along the EA, but the exact maximum sensitivity direction is perpendicular to that of the TMF magnetic moment M.

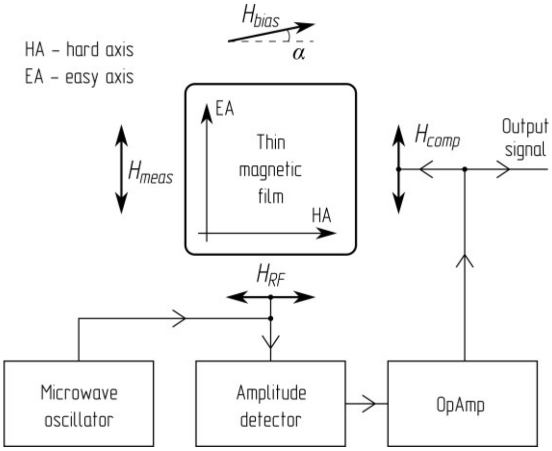


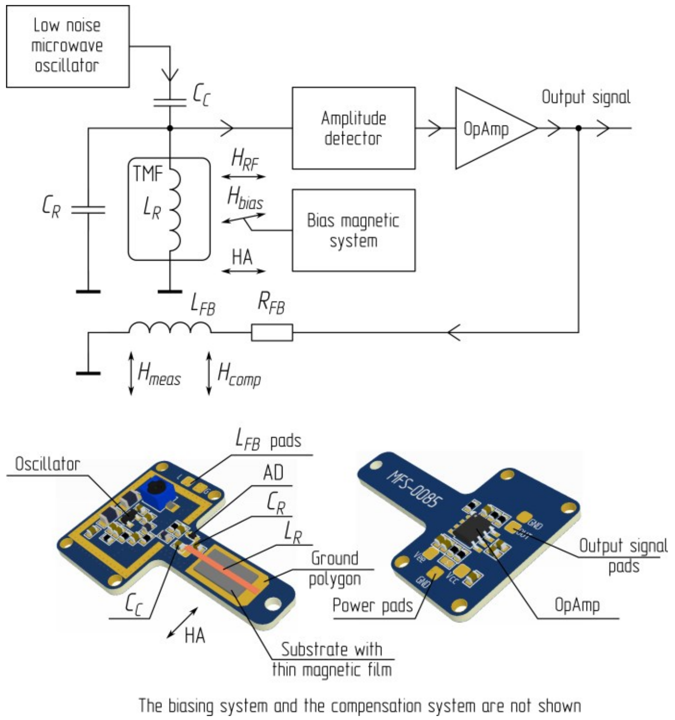
Fig. 2. The TMF-magnetometer block diagram: H_{meas} – measuring magnetic field; H_{bias} – biasing magnetic field; H_{RF} – excitation magnetic field; H_{comp} – compensation circuit magnetic field; EA – easy axis; HA – hard axis; α – angle between H_{bias} and HA

The compensation measurement method is used in order to improve the long-time stability of the magnetometer conversion factor. Determining precise maximum sensitivity direction setting can be achieved with a passive stabilization system made of ferromagnetic materials.

The sensor noise level is primarily defined by microwave oscillator amplitude noise. There are several possible oscillator designs. The first one is a low-noise and therefore low-power oscillator loosely coupled with the resonator. It allows creating the low-power magnetometer with total power consumption about 10^{-2} W for a three-axis transducer. Another one is an oscillator with additional power amplifier. An increase of excitation power makes the magnetometer conversion factor higher, but that results in the sensor power consumption. Another construction includes the oscillator transistor loading directly on the microstrip line. The resonator is a part of oscillator and its frequency needs no adjustment to resonance in this case.

The amplitude detector (AD) output signal has a direct component, which is proportional to the oscillator amplitude, and a low-frequency component, which reflects the measured magnetic field H_{meas} changing. The AD is usually realized as half-wave rectifier including a low-noise high frequency diode and a low-pass filter. The AD output signal is applied to an operational amplifier (OpAmp) loaded by a compensation coil. The compensation coil is connected to the OpAmp feedback loop through a high-precision and temperature stable resistance. The magnetometer conversion factor is determined by the compensation coil constant and value of the feedback resistance. It is important to provide those components with long-time stability.

The stand-alone magnetometric transducers include the TMF in the microstrip resonator; the microwave excitation oscillator; the amplitude detector; the operational amplifier; the biasing magnetic system; the compensation system and the power supply system. There are several possible magnetometer design types, the simplest design is shown in the Fig. 3.



The biasing system and the compensation system are not shown

Fig. 3. The TMF-magnetometer functional diagram and printed circuit board construction: C_R – resonator capacitor; C_C – coupling capacitor; L_R – resonator inductance; L_{FB} – feedback inductance of compensation circuit; R_{FB} – feedback resistance

The generator with a low noise transistor excites oscillations in the microstrip resonator through a coupling capacitor C_c. The resonator inductive part L_R is located over the ceramic substrate with the TMF and produces the high frequency excitation magnetic field H_{RF} along the HA. The biasing magnetic field direction determines a magnetometer operation mode. In any mode the H_{bias} amplitude is more than the TMF anisotropy field and the TMF is in a single-domain state. When H_{bias} field is directed along the HA and the H_{RF}, there are no conditions for FMR to excite. The magnetic moment M is along the HA. The measuring field H_{meas} is directed along the EA and it deflects the magnetic moment from the HA resulting in creating FMR conditions (Fig. 4, a). The magnetic susceptibility tensor components change following the equilibrium magnetic moment direction changing. Thus, the measured field causes complex magnetic permeability changing. The real permeability part influences the imaginary part of insertion impedance and the permeability imaginary part brings loss resistance to the resonator. The operation principle of the TMF-magnetometer is based on TMF loss inserting to the resonator. Hence, TMF absorbs high frequency energy in the resonator, that is detected by AD.

Increasing the angle α between HA and H_{bias} makes the second harmonic of AD signal decrease and the first harmonic occur (Fig. 4, b).

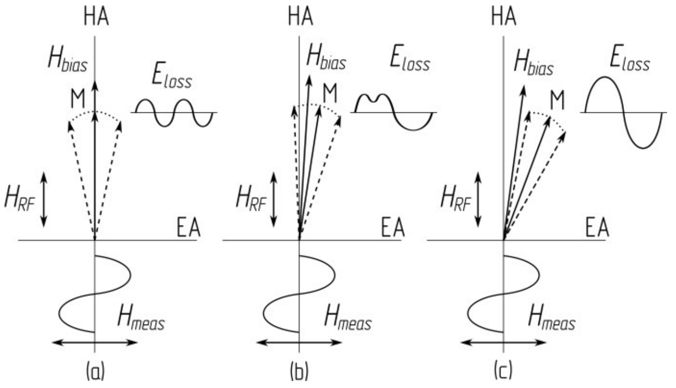


Fig. 4. The TMF-magnetometer operation modes:a – frequency doubling mode; b – transient mode; c – operating mode. E_{loss} – TMF high-frequency energy loss

Further increasing the angle α results in the magnetometer conversion factor increase (Fig. 4, c). There is an optimal angle α when the conversion factor is maximal and the sensor works in a linear mode. As a rule, the angle α lies between 5 and 10 degrees.

III. CONCLUSIONS

The presented TMF-magnetometer has several distinctive features: wide frequency bandwidth with a constant conversion factor; high sensitivity and low noise level at the room temperature; a small weight and size; low cost in mass production. The magnetometer has some advantages over known solutions (see fig. 1) and can be used in various applications: geomagnetic exploration; navigation systems, security systems, imaging systems, magnetic communication systems, and biomedical application. Table 1 exemplifies the TMF-magnetometer typical characteristics for geomagnetic exploration.

TABLE I. THE TMF-MAGNETOMETER CHARACTERISTICS

Parameters		***Value***	***Unit***
Noise level, max	at 1 Hz	10^{-11}	T
	10^2 Hz and higher	$5 \cdot 10^{-13}$	
Frequency band		$10^{-2} \ldots 10^5$	Hz
Power consumption, max		1	W
Overall dimensions		20x30x15	mm
Weight		20	g

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