

Detection of inhomogeneous magnetic fields using magnetoelectric composites

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Abstract

Magnetoelectric (ME) composites have a wide range of possible applications, especially as room-temperature sensors of weak magnetic fields in magnetocardiography and magnetoencephalography medical diagnostic equipment. In most works on ME composites, structures are tested in uniform magnetic fields; however, for practical application, detailed knowledge of their behaviour in inhomogeneous magnetic fields (IMFs) is necessary. In this work, we measured IMFs with radial symmetry produced by alternate currents (AC) passing through an individual thin wire upon different placements of an ME sensor. An ME self-biased b-LN/Ni/Metglas structure with a sensitivity to the magnetic field of 120 V/T was created for IMF detection. The necessity of an external biasing magnetic field was avoided by the inclusion of a nickel layer having remanent magnetization. The ME composite shows a non-zero ME coefficient of 0.24 V/(cm · Oe) in the absence of an external DC magnetic field. It is shown that the output voltage amplitude from the ME composite, which is located in an AC IMF, is dependent on the relative position of the investigated sample and magnetic field lines. Maximum ME signal is obtained when the long side of the ME sample is perpendicular to the wire, and the symmetry plane which divides the long side into two similar pieces contains the wire axis. In the frequency range from 400 Hz to 1000 Hz in the absence of vibrational and other noises, the detection limit amounts to $(2 \pm 0.4) \text{ nT/Hz}^{1/2}$.

Keywords

magnetoelectric effect, composite structures, biasing layer, bidomain lithium niobate, metglas, nickel, inhomogeneous magnetic field

1. Introduction

The interest in magnetoelectric (ME) composites is caused by the wide range of their potential applications in various electronic devices [1]. One of the promising and most practically valuable applications is the use of

composite ME materials as ultra-weak magnetic field sensors [2–6] in medical equipment for magnetocardiography (MCG), magnetoencephalography (MEG) and magnetomicroscopy (MMG). These medical techniques are currently implemented by using sensors based on SQUID magnetometers or optically pumped ones impos-

ing strict limitations on the operation temperature range. It was shown earlier that the magnetic field of the cardiac muscle can be successfully detected with an AlN/Si/Metglas ME composite sensor [7]. The use of ME sensors is expected to reduce the cost of MCG, MEG and MMG equipment due to the exclusion of bulky cooling systems from the equipment design and the capability of the new sensors to be operated in a wider dynamic range of magnetic field magnitudes with a higher spatial resolution. Successful implementation of ME composites in biomedical devices requires not only designing materials with a high ME coefficient but also solving a number of engineering tasks related to optimization of the operating frequency range (neuron activity can be detected at frequencies below 1 kHz), extraction of the useful signal from high-density noises of various nature [8] and reduction of the dimensions and power consumption of the sensors without a compromise in the sensitivity. The sensor performance can be improved by varying the form factor of ME specimens [9], experimenting with various combinations of piezoelectric (PE) materials (e.g., AlN [10,11], AlScN [12], PZT [13]) and magnetostrictive (MS) layers (e.g., Metglas [5, 14–20]), obtaining non-zero ME effect without an external biasing DC magnetic field using different methods [14, 21–23], and comparing different specimen attachment configurations (free clamping, cantilever and bi-cantilever attachment [24, 25]).

Most often, the ME properties of composites are measured in spatially homogeneous magnetic fields (HMF). However, this approach is suitable for recording the frequency response of magnetic field sensitivity for research purposes. Practical sensor applications imply operations in spatially inhomogeneous magnetic fields (IMF). One of the common tasks in the studies of IMF is mapping the spatial distribution of the magnetic field intensity. In this case, along with the ME sensitivity, it is of great importance to choose the correct dimensions and shape of the sensor used, as well as the position of the latter relative to the magnetic field lines. Neglect of these factors can

lead to ambiguous results. For example, a study of the spatial distribution of magnetic field intensity of a single winding turn using an ME composite specimen [26] showed that the dependence of the detected signal on the sensor position relative to the winding turn changes with the AC frequency in the winding turn, and at some sensor positions, the signal tends to zero. Attention to all these factors and a profound analysis of the reciprocal task of field mapping with a FeCoSiB/Si/AlN ME composite-based sensor [27] allowed Friedrich et al. to restore the image of a text written on a substrate with core-shell type magnetite nanoparticles.

Below we will analyze experimental measurement data for a radially symmetrical IMF generated around a thin single wire carrying AC, at different positions of the ME sensor relative to the single wire. The choice of IMF source was dictated by the similarity of magnetic field intensity distribution around the wire with the magnetic field of single neurons [28]. According to our information, no such measurements have been carried out so far. The ME response was measured at different positions of the specimen relative to the single wire.

2. Experimental

The IMF of a conductor carrying AC was measured with a 2-2 type trilayer gradient ME composite with a bidomain lithium niobate crystal (b-LN) as a PE layer, Metglas as a MS layer and nickel as a magnetizing layer.

A “head-to-head” type bidomain structure was formed in a $Y+128^\circ$ cut lithium niobate crystal by annealing near the Curie point with out-diffusion (reverse diffusion) of lithium oxide, the choice of the cut orientation was dictated by the high lateral PE modulus $d_{23(Y+128^\circ)} \approx 26 \text{ pm/V}$ [29]. The dimensions of the b-LN crystal were $20 \times 5 \times 0.5 \text{ mm}^3$. One side of the b-LN plate was electrochemically coated with a 10 mm thick nickel layer, the electrode was a thin titanium film (150 nm) which was

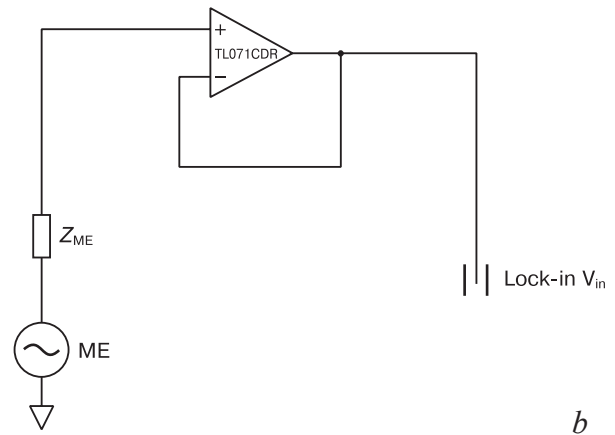
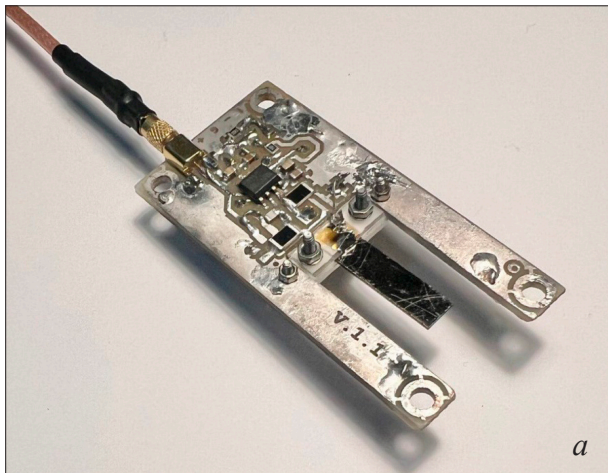


Figure 1. (a) Appearance and (b) electric circuit of a ME structure in holder placed on PCB (designations in the figure: ME is the magnetoelectric output signal, Z_{ME} is magneto-electric-structure impedance, TL071CDR is an operational amplifier and Lock-in V_{in} is the lock-in amplifier input voltage)

preliminarily deposited by magnetron sputtering. To create remanent magnetization, the b-LN/Ni structure was annealed in a 2500 Oe DC magnetic field at 380 °C for 2 min by a method suggested earlier [30]. At the final stage of the ME composite preparation, the b-LN structure was coated with a 29 mm thick 2826MB Metglas foil (Hitachi, Japan).

For the measurements, the specimen was cantilever-clamped in a holder between two single-crystal sapphire plates and attached to a printed circuit board with through-holes and a pre-amplifier (a TL071CDR operational amplifier, ST Microelectronics, US). The TL071CDR model was chosen due to a combination of availability, low voltage noise and low input current. A photo of the printed circuit board (PCB) and an electrical circuit of the amplifier are shown in Fig. 1. For measurements the PCB was screened from external interferences by a grounded aluminium box.

The frequency dependence of the ME coefficient for the specimen was studied in an AC HMF that was generated by Helmholtz coils. The frequency and amplitude of the magnetic field intensity in the coils were set by the generator of a MFLI lock-in detector (Zurich Instruments, Switzerland) the signal of which was amplified with an AE Techtron 7224 (4-quadrant power amplifier, AE Techtron, USA) unit. The ME signal generated by the specimen was fed to the voltage repeater as described above and then to the measurement circuit of the synchronized detector. This setup allowed measuring the ME response in quasi-static and dynamic modes [30].

Quasi-static measurements were carried out to find the bias of the field dependence of the ME coefficient caused by remanent magnetization of the nickel layer, evaluating the ME coefficient in the absence of an external DC magnetic field and comparing it with the ME coefficient at the optimum intensity of the DC magnetic field. The DC magnetic field intensity was changed in the –25 to +25 Oe range with the simultaneous application of a sine AC component for magnetic field modulation with a 0.1 Oe amplitude at a frequency of 117 Hz.

Then the test b-NL/Ni/Metglas ME specimen was studied in dynamic mode for retrieving the frequency dependence of the ME coefficient. The measurements were conducted in a sine AC magnetic field (0.1 Oe, 10 Hz – 1 kHz, 5 Hz step). No DC biasing magnetic field was applied.

3. Description of the measurement setup and characterization of the ME gradient structure

The IMF source was a 0.2 mm diameter, 40 cm long copper wire. AC currents of 0, 5, 10 and 50 mA were fed from the MFLI lock-in with a connected 100 Ohm current-limiting resistor. To eliminate the influence of the inductive component of the circuit we measured the impedance of the wire-resistor system which proved that the inductance of the circuit is low in the operating frequency range (10–1000 Hz), the full wire-resistor system impedance being 100 Ohm. The pre-amplifier PCB with the ME specimen was arranged in a screening box in the required position relative to the wire using a Thorlabs three-axis positioner manually controlled with micrometer screws. All the measurements were conducted with a lock-in filter bandwidth of 1 Hz.

4. Results and discussion

4.1. Magnetoelectric parameters of the b-LN/Ni/Metglas structure

The results of quasi-static measurements are shown in Fig. 2.

The highest ME coefficient of the structure (1.96 V/(cm · Oe)) was achieved at a DC magnetic field of –7.5 Oe in quasistatic regime. Without an external

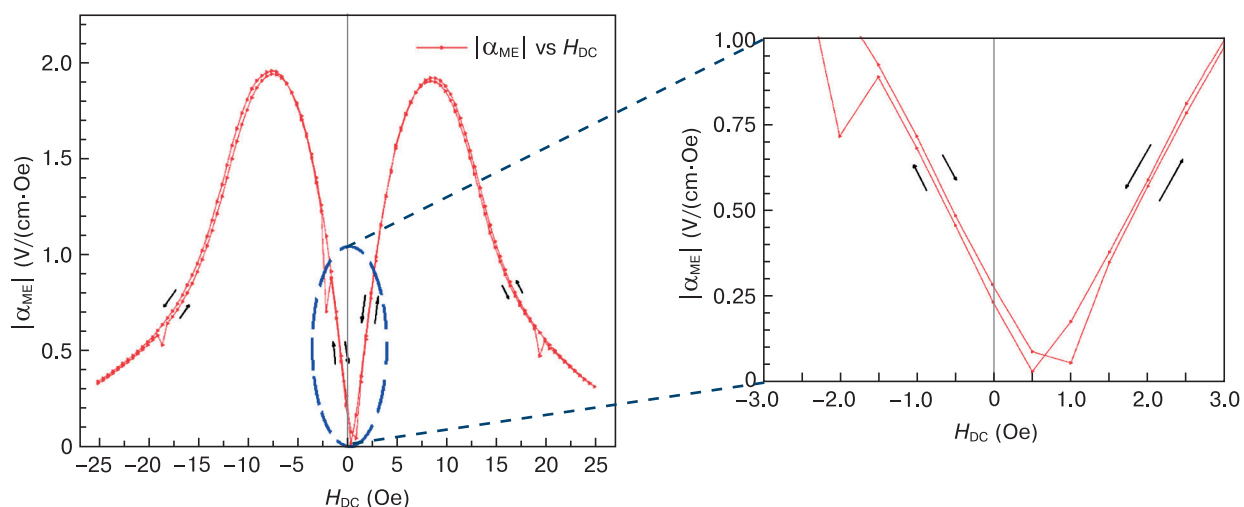


Figure 2. ME coefficient of the b-LN/Ni/Metglas structure as a function of DC magnetic field amplitude

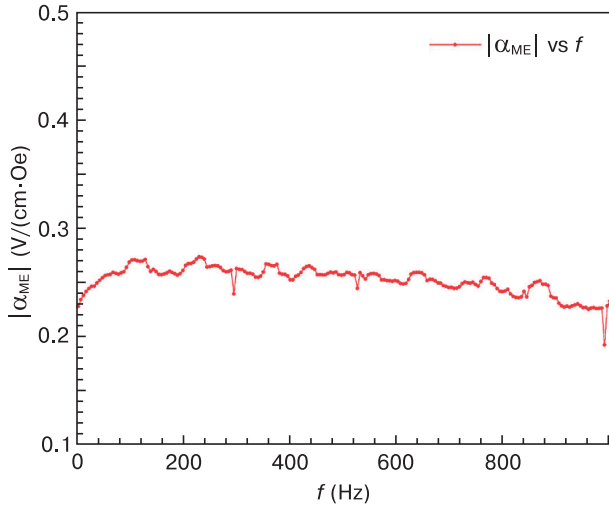


Figure 3. ME coefficient of the b-LN/Ni/Metglas structure as a function of frequency without external DC magnetic field

DC magnetic field, the ME coefficient of the test specimen was a non-zero one of 0.24 V/(cm · Oe) (Fig. 2 b). Noteworthy, the field dependence of the ME coefficient was shifted relative to zero by 0.5 Oe which is comparable with the magnetic field of the Earth. Therefore, to eliminate the contribution of the Earth's magnetic field, we arranged the specimen in all the experiments reported herein so that the Earth's field lines were perpendicular to the specimen's longer side.

Dynamic ME coefficient measurements for the test composite were conducted without an external DC magnetic field, i.e., biasing was only provided by the remanent magnetization of the nickel layer. Dynamic measurement data are shown in Fig. 3.

The ME coefficient of the b-LN/Ni/Metglas structure varied in the 0.22 to 0.26 V/(cm · Oe) range for frequencies from 10 to 1000 Hz. The average ME specimen sensitivity in the quasi-linear range (10–1000 Hz) was $S_{av} = 120$ V/T which is comparable with earlier data, i.e., an 856 V/T value reported for the bending resonance frequency of a Si/MnIr/Metglas/AlN structure [31], and a 600 V/T value obtained for a Metglas/Pb(Zr,Ti)O₃ specimen beyond the structure resonance frequencies (at 1 kHz) [32].

4.2. Simulation of the 3D magnetic field distribution for a single wire

The 3D magnetic field distribution for an infinite single wire was simulated in the COMSOL Multiphysics environment. Three specimen position options relative to the wire were considered in the model as shown in Fig. 4. In all cases the specimen plane coincided with the *XY* plane, and the *Z*-axis distance between the ME specimen and the wire was 13 mm since this distance was the minimum possible one for the screening box used. In Position A the wire was arranged parallel to the longer side of the spec-

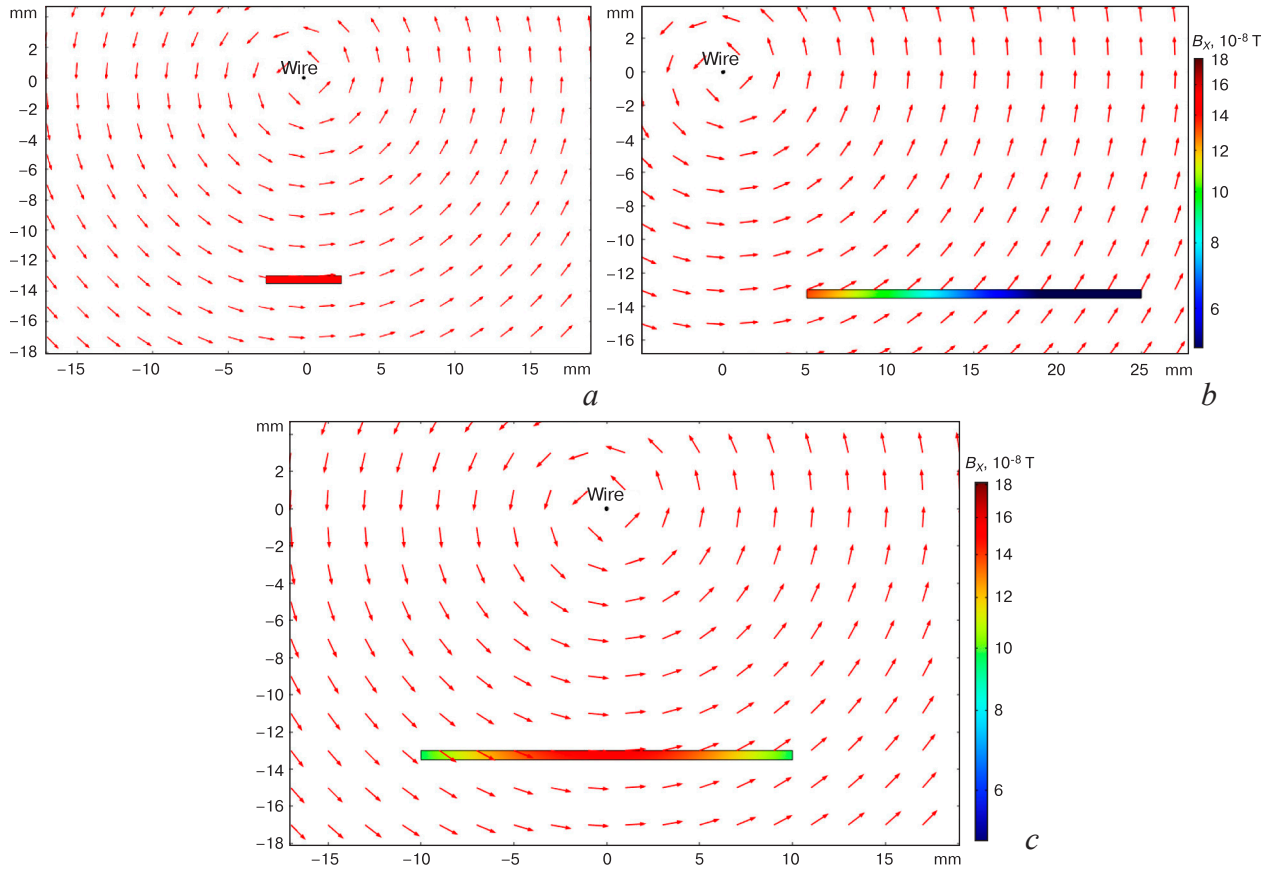


Figure 4. Visualization of simulation results for magnetic field intensity of a single wire near the ME specimen in Positions (a) A, (b) B and (c) C. Arrows show magnetic induction vector directions in the points

imen, in Position B the longer side of the specimen was perpendicular to the wire, the distance between the wire and the specimen end was 5 mm, and in Position C the longer side of the specimen was also perpendicular to the wire but the middle of the longer side was on the Z-axis. The AC amplitude in the copper wire was taken to be 10 mA for the model.

The simulation of the magnetic induction vector component B_X distribution along the X -axis in the specimen section is shown in Fig. 4.

Since the ME specimen has the form of a thin and narrow plate cantilever-clamped along the X -axis, the greatest contribution to the ME response comes from the magnetic induction vector component along the X -axis. In this direction, the magnetic induction gives the greatest contribution to the ME coefficient and magnetostriction since the ME coefficient is directly proportional to the length of the working part of the structure [24, 33] and the lithium niobate crystal was cut so that its longer side was in the direction of the highest transverse PE coefficient. Thus, for the same electric current in the wire, the ME signal must be the greatest in Position B and the smallest in Position A.

4.3. Measurement of the inhomogeneous magnetic field of a single conductor

The response of the b-LN/Ni/Metglas ME specimen in an AC IMF of a single wire was measured in Positions A, B and C used for simulation. In each of these positions relative to the wire, the ME signal was detected for a sine AC through the wire with amplitudes of 5, 10 and 50 mA in the 10 Hz to 1 kHz frequency range. The spectral densities of the background electromagnetic and acoustic noise

induced in the specimen were evaluated by measuring the ME response without current in the wire. Furthermore, to estimate the electromagnetic interferences at the specimen and the PCB, the response of a blank monodomain lithium niobate crystal sample with deposited electrodes but without an MS layer was measured for all the specimen positions. The measurement results are shown in Fig. 5.

In Position A (Fig. 5 *a*) the frequency dependence of the ME specimen signal exhibited a nonlinear pattern, with the response amplitude increasing with AC frequency. Since this position of the ME composite specimen relative to the wire was not optimum, the signal has far lower amplitude compared with those in Positions B and C. Nevertheless, for an AC amplitude of above 50 mA, the signal was greater than the intrinsic noise of the measuring circuit and the external interferences and could be reliably detected in the entire experimental frequency range. At AC amplitudes of 20 and 10 mA, the effective signal of the ME specimen could only be detected above 400 Hz.

For specimen positions B and C (Fig. 5 *b* and *c*), there was a linear dependence of the structure output signal on the AC frequency.

For Position C (Fig. 5 *c*) the noise level detected from the ME blank sample was far lower (by an order of magnitude) than the signal of the ME structure for a 5 mA AC if the signal was fed to a single wire ($V_{ac} = 0$, $I = 0$). One can therefore state that the signal detected by an ME sensor from a single conductor was authentic and contained but a little contribution from external oscillation noise and electromagnetic interferences. However, if the amplitude of the AC in the conductor was 50 mA the electromagnetic interference level for a blank sample became

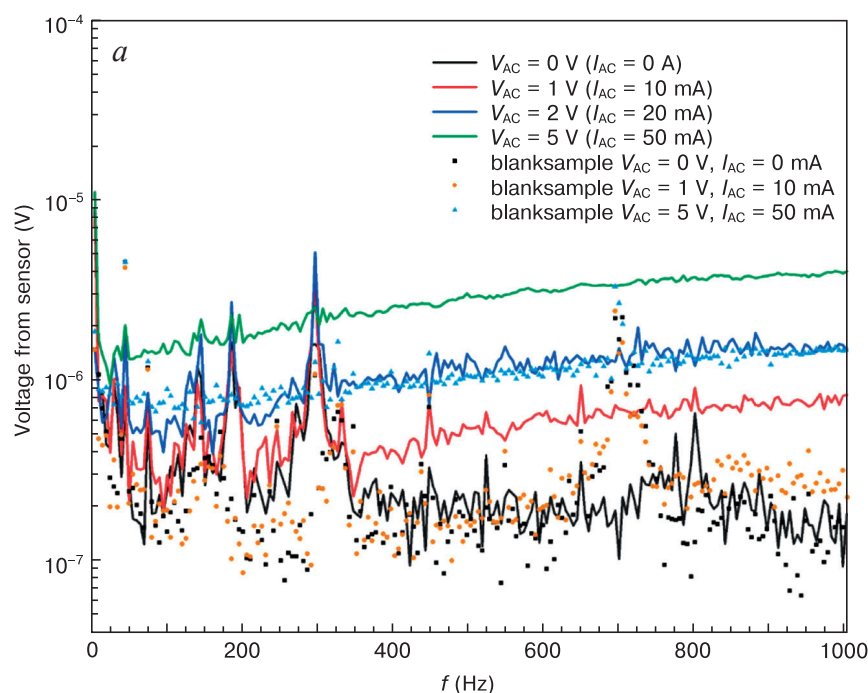


Figure 5. (Continued on next page)

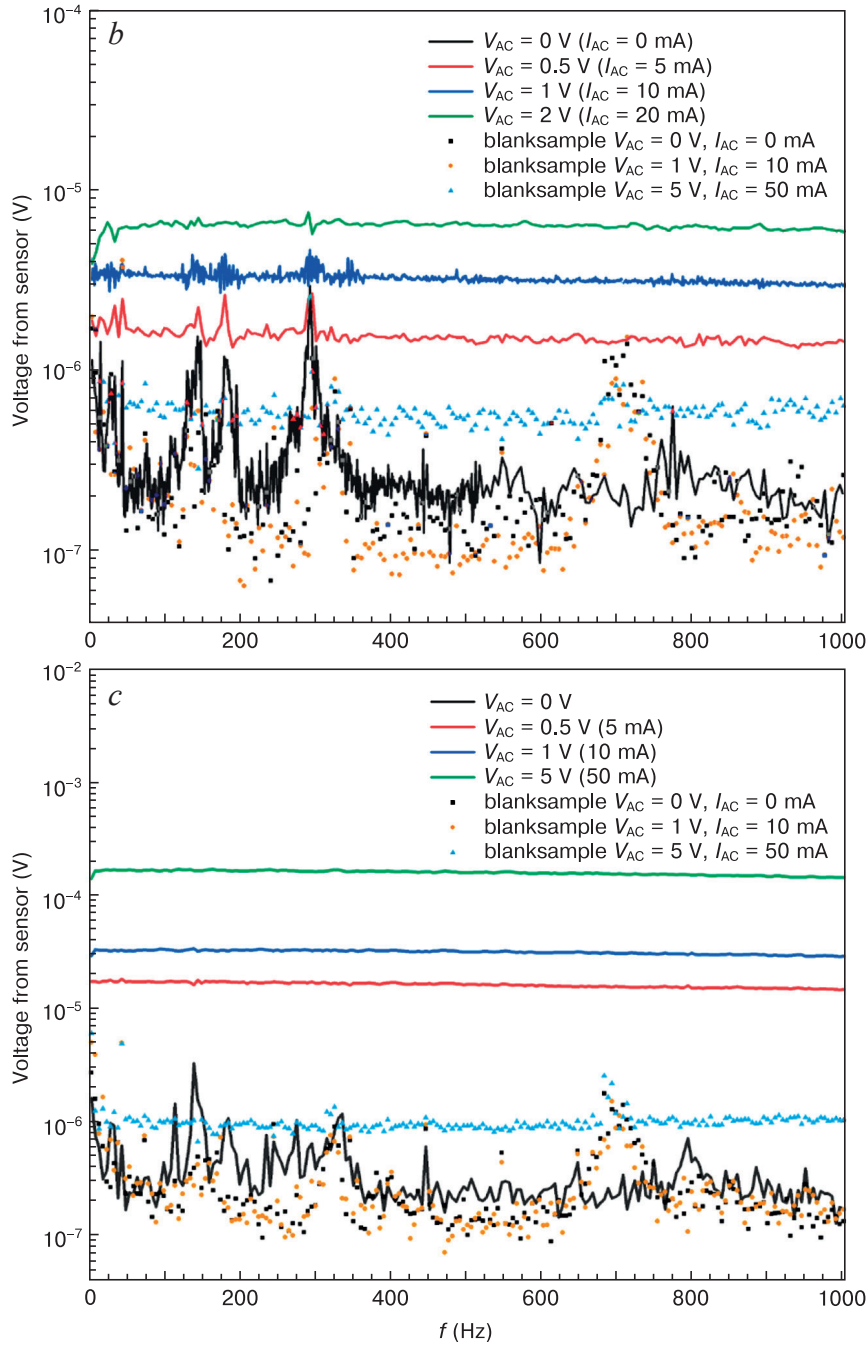


Figure 5. The magnetic field of a wire measured with the ME structure and the signal of a blank sample in Positions (a) A, (b) B and (c) C

greater than the noise level (the induced signal voltage was above $1 \mu\text{V}$). Then the Faraday electromagnetic induction and the eddy currents induced in the specimen and the measuring circuit could not be separated from the effective ME signal [34]. However, this parasitic interference is small compared with the effective signal of the ME specimen. For example, at an AC amplitude of 50 mA in the wire, the ME specimen signal was above $150 \mu\text{V}$ which is several orders of magnitude higher than the interference signal. Thus, the parasitic signal can be ignored. Similar conclusions can be drawn for Position B of the ME specimen relative to the single conductor.

In Position C of the ME structure relative to the single conductor, the ME signal amplitude was $\sim 30 \mu\text{V}$ for an AC amplitude of 10 mA which corresponds to the average magnetic field ($B_{av} = V_{ME}(10\text{mA})/S_{av}$) applied to the ME structure along the specimen. According to the simulation results shown in Fig. 4, c, the average projection of magnetic field induction B_{mod} on the longer side of the specimen is about 127 nT.

The average projection of magnetic field induction on the X -axis of the ME specimen in Position B is 74 nT (model), and the calculation from the experimental result, taking into account the sensitivity of the ME sample,

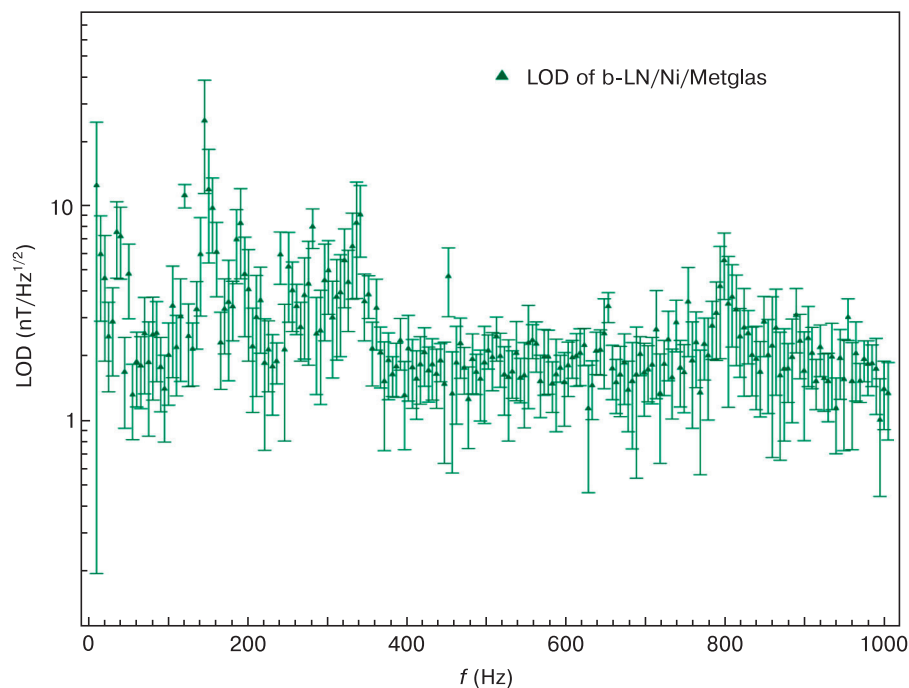


Figure 6. Spectral density of magnetic field LOD for b-LN/Ni/Metglas gradient ME composite structure

gives a value of 28 nT for an alternating current amplitude in the wire equal to 10 mA.

The difference between the experimental (B_{av}) and simulated (B_{mod}) magnetic field values can be accounted for by a combination of different factors:

- sensitivity S_{av} measurement error;
- inexact measurement of the spatial coordinate of the specimen during its positioning relative to the wire (the screening box does not allow precision visual control of the sensor positioning relative to the wire);
- the estimates presented above take into account only the magnetic induction field projection on the axis coincident with the longer side of the specimen.

Therefore we admit either underestimation or overestimation of the results. Furthermore, neither the processing of experimental data nor simulation allowed for the effects of gradient structure demagnetization and the remanent magnetization of nickel on the ME response of the specimen in the IMF. These factors will be given a profound analysis in further works to develop a model providing a more precise simulation of experimental results.

The minimum signal that can be detected by the ME specimen used in this work was evaluated by calculating the frequency response of the limit of detection (LOD) from the experimental data. The LOD chart obtained (Fig. 6) shows the limit sensitivity of the ME specimen under experimental conditions to an external AC magnetic field. One can see the effect of low-frequency oscillation noise producing peaks in the 130–160 Hz range

having an intensity up to 11 nT/Hz^{1/2}. In the 400 Hz to 1 kHz range where the effect of the oscillation noise and other interferences is but moderate, the LOD of the structure amounts to 2 ± 0.4 nT/Hz^{1/2}.

5. Conclusions

The ME composite b-LN/Ni/Metglas exhibits non-zero ME coefficients 0.22 and 0.26 V/(cm · Oe) in the absence of an external DC magnetic field and an average sensitivity to the magnetic field of 120 V/T, comparable to the results reported in [31]. It was demonstrated that the amplitude of the output signal from the ME composite in IMF depends on the relative orientation of the sample and the magnetic field lines. The largest signal is obtained when the long side of the ME sample is perpendicular to the current conductor, and the symmetry plane, dividing the long side of the sample in half, contains the axis of the conductor. In the future, it is planned to carry out magnetic field mapping from a single wire to determine the spatial resolution of the proposed IMP sensor.

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