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Magnetomodulation sensor of a weak magnetic field based on HTS $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ ceramics

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Abstract

We studied the possibility to develop the magnetomodulation sensor of weak magnetic field based on the HTS $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ ceramics with the operational temperature ~77 K and critical temperature ~105 K. The sensors involved two coils (excitation and signal ones), which were closely wound on a cylindrical HTS ceramic core. The core length was 10 mm, and the core diameter was ~2.5 mm. It was found that the magnetic sensitivity S_U ($S_U = dU_2/dH_0$, where U_2 is the second-harmonic signal) for such sensors depends on the excitation frequency in the range ~1–50 kHz, and on the excitation current I_{ac}. For the excitation current ~25 mA and excitation frequency ~50 kHz, the highest value of sensitivity $S_U \sim 390$ V/T was attained. When estimating the weakest magnetic field, which was detected by the sensor fabricated, we made allowance for the noise characteristics and errors of measurement devices used. The weakest detected field was ~0.5 nT in the absence of shielding from the terrestrial magnetic field and from the magnetic fields, which corresponded to industrial noise.

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Keywords: HTS ceramic $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$; Weak magnetic field; Terrestrial; Magnetic field; Magnetomodulation sensor of a weak magnetic field; Magnetosensitivity

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1. Introduction

Currently, weak magnetic fields $B \leqslant 10$ nT are measured using different magnetometers. Among them, the SQUID-devices are the most sensitive ones. However, they detect only the increment of the measured magnetic field. The flux-gate sensors and numerous magnetometers based on them can measure the absolute value of the magnetic field [1]. However, their measurement error in a region of weak fields $\mu_0 H_0 \leqslant 1$ nT ($\mu_0 = 4\pi 10^{-7}$ H/m) increases, and they have narrow transmission band ($\leqslant$10 kHz) and dynamical measurement range ($\leqslant$60 dB).

High-temperature superconducting ceramics (HTS) consists of numerous grains, and the Josephson transitions are formed between their boundaries. This Josephson medium has strongly nonlinear magnetic sensitivity. This circumstance is used in the magnetosensitive sensors. Virtually all magnetometers were fabricated based on the HTS Y–Ba–Cu–O ceramics. At operational liquid-nitrogen temperature, these materials are not far from the critical state (the critical temperature ~90 K). Therefore, they have high magnetosensitivity [2,3]. However, these materials have a substantial disadvantage of degradation during storage in air under standard conditions.

In this work, we investigated the possibility to fabricate a magnetomodulation sensor of a weak magnetic field based on the HTS $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ ceramics with the operational temperature $T \sim 77$ K.

2. Sample preparation and experimental results

Ceramic samples were fabricated from the prepared HTS $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ powder as the pellets of diameter

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15 mm and 4 mm thick. The samples were annealed in a furnace. The temperature gradually elevated with the rate 100 °C/h to the temperature of the main anneal 855 °C. The annealing time t_{ann} of the samples was ~40, ~80, ~120, and ~240 h. After the anneal at temperature 855 °C was completed, the samples were cooled with the rate 100 °C/h and extracted from the furnace. The rods for the sensors of a weak magnetic field and the wafers to carry out the reference measurements were cut from the samples.

Sensors, which were fabricated by standard ceramic technology, had a low critical current density ($\leqslant 10\ \text{A/cm}^2$) and a high critical temperature ($\geqslant 103$ K). All measurements were carried out at liquid-nitrogen temperature without shielding the terrestrial magnetic field. The sensor (the axis of the cylindrical rod) was arranged upright. The measured weak magnetic field H_0 was induced using the Helmholtz coils. The directions of the magnetic fields H_0 and the excitation magnetic field H_{ac} were collinear ($H_0 \| H_{\text{ac}}$) or normal ($H_0 \perp H_{\text{ac}}$). All measurements were carried out at $T = 77$ K.

The cylinder-shaped sensors were ~12–13 mm in length with the diameter ~2.5 mm. Two coils, namely the excitation and signal ones, were closely wound around the rods over the length 10 mm. The excitation coil consisted of two identical back-to-back sections, each section of 200 turns. The signal coil of 400 turns was wound over the excitation coil. The magnetosensitivity was determined as $S_U = \mathrm{d}U_2/\mathrm{d}H_0$, where U_2 is the signal of the second harmonics.

Fig. 1 shows the dependences $U_2(H_0)$ for a typical sensor with $t_{\text{ann}} \sim 40$ h, the excitation current $I_{\text{ac}} \sim 8$ mA, corresponding alternating excitation magnetic field $\mu_0 H_{\text{ac}} \sim 400\ \mu\text{T}$, ($H_0 \| H_{\text{ac}}$), and various excitation frequencies f_{ac}. One can see that the plots $U_2(H_0)$ fit well the straight lines, and their slope increases as the excitation frequency f_{ac} increases. It is noteworthy that the output signal is substantial in the absence of the external magnetic field, i.e., for $H_0 = 0$. Such behavior is mainly caused by the existence of the terrestrial magnetic field and a strong signal of sensor disbalance. The S_U magnitude remains virtually constant in magnetic fields ±50 μT, and in the fields ±(50–700) μT it gradually decreases by 40–50% from a highest value as H_0 increases.

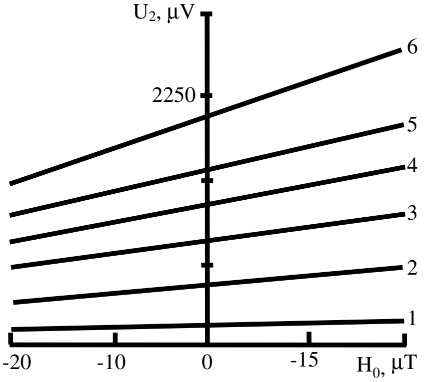

Fig. 1. Dependence $U_2(H_0)$ for the sample $t_{\text{ann}} \sim 40$ h at $I_{\text{ac}} = 10$ mA and various f_{ac}, (bottom-up): 1–5 kHz; 2–10 kHz; 3–20 kHz; 4–30 kHz; 5–40 kHz; 6–50 kHz.

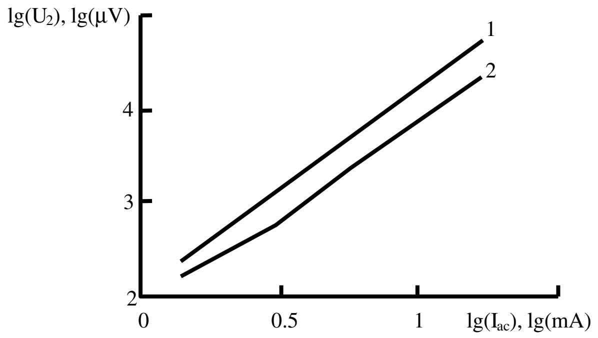

Fig. 2. Dependence $U_2(I_{\text{ac}})$ in the logarithmic scale for the sample with $t_{\text{ann}} \sim 80$ h at various H_0: 1 – $H_0 = 0$; 2 – $H_0 = 20\ \mu\text{T}$.

Fig. 2 shows the curves $U_2(I_{\text{ac}})$ at various H_0, ($H_0 \| H_{\text{ac}}$) and $f_{\text{ac}} = 50$ kHz for the sample with $t_{\text{ann}} \sim 80$ h. The evaluation of U_2 as a function of I_{ac} gives an approximate power dependence $U_2 \sim I_{\text{ac}}^{\alpha}$, where $\alpha \approx 2.1 \pm 0.2$. The exponent α increased in the limits of the mentioned error in the range $\mu_0 H_0 \sim (0\text{–}50)\ \mu\text{T}$. The highest value $S_U \sim 390$ V/T was obtained at $I_{\text{ac}} \approx 25$ mA, which corresponded to $\mu_0 H_{\text{ac}} \approx 1000\ \mu\text{T}$.

In the region of weak measured fields ($\leqslant 50\ \mu\text{T}$) and weak excitation fields ($\leqslant 500\ \mu\text{T}$), no hysteresis or nonlinearity are observed in the $U_2(H_0)$ curve. Fig. 3 shows typical curves $U_2(H_0)$, which were recorded for the sample annealed for $t_{\text{ann}} \sim 120$ h at ($H_0 \| H_{\text{ac}}$) and $f_{\text{ac}} = 50$ kHz in the increased (from −2500 to +2500 μT) and decreased (from +2500 μT to −2500 μT) magnetic fields. One can see that the highest hysteresis value is no higher than 60 μT. The effect of hysteresis on the magnitude of S_U is negligibly small.

The above results were obtained for a mode with $H_0 \| H_{\text{ac}}$. Fig. 4 shows the comparison of the plots $U_2(H_0)$ recorded at $H_0 \| H_{\text{ac}}$ and $H_0 \perp H_{\text{ac}}$ for the sample annealed for $t_{\text{ann}} \sim 120$ h. The ratio of the magnitudes S_U at $H_0 \| H_{\text{ac}}$ and $H_0 \perp H_{\text{ac}}$ for all samples was approximately identical and constituted 14–17.

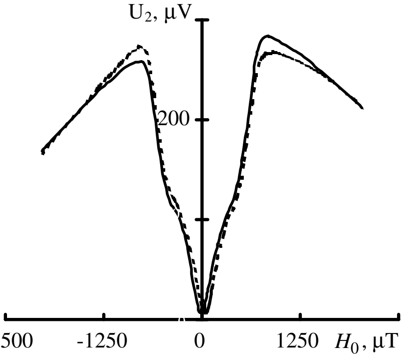

Fig. 3. Dependence $U_2(H_0)$ for the sample with $t \sim 120$ h for an increase (full) and for a decrease (empty) in H_0.