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Suppression of nonlinear magnetoelectric effect hysteresis in a layered ferromagnetic-piezoelectric structure

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ABSTRACT

Nonlinear magnetoelectric effect in a planar ferromagnetic-piezoelectric composite structure, placed in the constant magnetic field H and harmonic alternating field h, manifests itself in voltage harmonics generation. The hysteresis in the field dependence of magnetostriction of the ferromagnetic layer leads to an ambiguous dependence of the harmonic amplitudes on H. The effect of the hysteresis suppression in the harmonic amplitudes dependences on the field H under increasing amplitude of the excitation field is described in the paper. In a planar structure with Ni and lead zirconate titanate layers, an increase in the field h from 1 Oe to 100 Oe led to a decrease of the coercive field from 21 Oe to 0.4 Oe in the field dependence of the first and third voltage harmonics amplitudes. The simulation showed that the effect is caused by a decrease in the relative influence of the constant field on the asymmetry of the ferromagnetic layer magnetostriction loop of the structure with increase of the excitation field. The hysteresis suppression effect will increase the measurement accuracy of the magnetoelectric sensors.

1. Introduction

Magnetoelectric (ME) effects in planar composite structures, consisting of mechanically coupled ferromagnetic (FM) and piezoelectric (PE) layers, have been intensively studied in recent years for their promising applications in highly sensitive magnetic field sensors [1,2].

When a ME structure is placed in an external magnetic field, its FM layer deforms due to magnetostriction, this deformation is transferred to the PE layer which generates an electric voltage proportional to the field. To increase the sensitivity of the sensors, FM layers of the structures are usually made of materials with large magnetostriction, such as magnetic amorphous alloys, nickel, permendur, galfenol, terfenol, ferrites, etc. Various types of ac [3,4] and dc [5,6] magnetic field sensors were fabricated, allowing registration of magnetic fields with a minimum value down to ~30 pT [7]. The possibility of creating low-frequency (1–100 Hz) magnetic fields sensors using the nonlinear magnetoelectric frequency up-conversion effect [8–10], and dc magnetic field sensors based on the nonlinear ME effect of harmonics generation [11] was demonstrated. Noise characteristics of ME sensors which determine minimal detectable magnetic field have been investigated [4,12–13].

The hysteretic dependence of the FM layer magnetostriction on the constant field $\lambda(H)$ leads to an ambiguous field dependence of the voltage, generated by the structure $u(H)$. The coercive field for ferromagnetic layers, used in the structures, is H_c ~1 Oe for the amorphous alloy Metglas, ~20 Oe for nickel, ~30 Oe for ferrites, ~200 Oe for cobalt, and more than 100 Oe for terfenol. The magnetostriction hysteresis can be used to design ac ME magnetic field sensors, operating without a bias field [14,15], but it plays a negative role in dc ME magnetic field sensors, since the ambiguity leads to a catastrophic decrease in the absolute accuracy of measurements. In order to get rid of this disadvantage, it is necessary either to demagnetize the FM layer before each measurement, which in that case significantly complicates the sensor design, or to take a special calibration procedure to eliminate hysteresis. As far as the authors know, any methods of suppressing hysteresis in ME structures have not been discussed up to now.

In the present paper it is shown for the first time that the problem of hysteresis can be solved in ac magnetic field sensors using the nonlinear ME effect of voltage harmonics generation. It has been experimentally demonstrated that an increase in the amplitude of the excitation field leads to suppression of the hysteretic dependence of the generated voltage harmonics amplitudes on the measured dc field. The hysteresis loop width in the dependence of the output signal on measured field is reduced by ~2 orders of magnitude for a structure containing a magnetostrictive layer of

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nickel, which increases the absolute accuracy of the field measurement by the same amount.

2. Sample and experiment

The investigated planar composite structure is schematically shown in Fig. 1. It contains a FM layer of nickel (Ni) with dimensions of 5 mm × 15 mm and a thickness of 0.2 mm and a PE layer of lead zirconate titanate ceramics (PZT-5) with dimensions of 5 mm × 15 mm and a thickness of 0.5 mm. The choice of nickel as a FM layer of the structure is due to the fact that it has a sufficiently large saturation magnetostriction $\lambda_S = -30$ ppm in relatively low fields $H_S \sim 0.5$ kOe and has a noticeable coercive field $H_c \approx 21$ Oe, which is important for effect demonstration. The PZT layer has 3 μm thick Ag electrodes on the planes, dielectric constant ε = 1750 and piezoelectric module d_{31} = 175 pC/N. The layers were connected to one another under the press using the epoxy adhesive.

The structure was placed inside a solenoid with diameter of 15 mm and length of 50 mm fed by an alternating current $I(t)$ with amplitude up to 2 A. The solenoid created an ac excitation magnetic field with frequencies f from 10 Hz to 200 Hz and an adjustable amplitude up to h = 100 Oe. A constant bias field H = 0–500 Oe produced by the Helmholtz coils was applied along the long axis of the structure. The constant and alternating fields were measured by a gaussmeter model 421 (Lake Shore, USA) with accuracy of 0.1 Oe. The structure was air-cooled to prevent heating during the measurements and the temperature was monitored with a thermistor attached to the FM layer. The frequency spectrum of the voltage u(f) generated across the electrodes of the PE layer due to the ME effect was registered with a spectrum analyzer SR770 (Stanford Research, USA). Measurements were carried out in the non-resonant regime at the excitation field frequency much lower than the resonance frequencies of the bending and planar acoustic oscillations of the structure. The dependences of the voltage harmonics amplitudes as a function of the excitation field amplitude h for constant bias fields H and the dependences of the voltage harmonics amplitudes as a function of the field H for various excitation fields h were measured.

3. Linear magnetoelectric effect

When the structure is undergoing a weak alternating magnetic field $h(f) = h\cos(2\pi ft)$ and a permanent magnetic field H, it generates an alternating voltage $u\cos(2\pi ft)$ with the same frequency due to ME effect [16]. The dependence of the ME voltage amplitude u on the constant field $u(H)$, measured at the excitation field h = 1 Oe and frequency ∼120 Hz is shown in Fig. 2a. The dependence has a typical form for the linear ME effect: u initially increases linearly with increasing H, reaches a maximum at $H_m \approx 80$ Oe, and then smoothly decreases when the FM layer is saturated in large fields. The maximum u is observed in the field at which the piezomagnetic coefficient of the FM layer $q = \partial\lambda/\partial H$ (where $\lambda(H)$ is the magnetostriction) reaches its maximum. The maximum value of the linear ME coefficient for the described

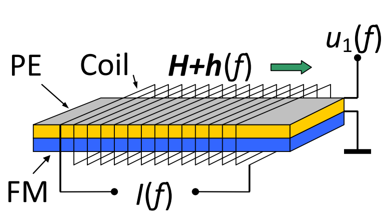

Fig. 1. Schematic view of the composite ferromagnetic-piezoelectric structure.

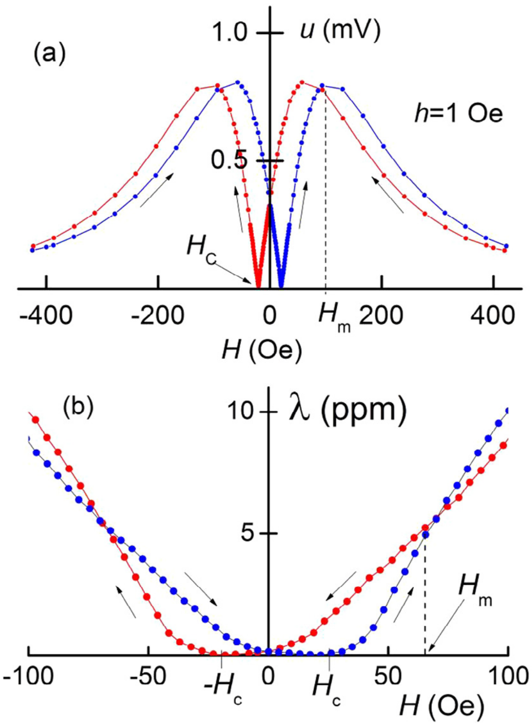

Fig. 2. (a) Dependence of ME voltage generated by the Ni-PZT structure on H for h = 1 Oe, f = 120 Hz; (b) Hysteretic dependence of magnetostriction λ on H for the Ni plate.

structure was $\alpha_E = u/(hb)$ = 16 mV/(Oe·cm). The Hysteretic dependence $u(H)$ is noteworthy: the curves do not coincide under a cyclic increase and decrease of the magnetic field H, the structure demonstrates residual ME effect at H = 0, and the voltage drops to zero at fields $H_C \approx \pm 21$ Oe. As it was shown earlier, the hysteretic dependence of the linear ME effect amplitude arises from the hysteresis in the dependence of the magnetostriction on the field H for the FM layer [15,17].

To confirm this fact, Fig. 2b shows the dependence of the Ni layer magnetostriction on the constant field in the region $|H| \leq 450$ Oe. The dependence was measured by the strain gauge using automated setup at the magnetic field change rate $\partial H/\partial t = 10$ Oe/s. It is seen that the magnetostriction does indeed drop to zero at fields $Hc \approx \pm 21$ Oe, and the maximum of the piezomagnetic coefficient (the slope of the curve $q = \partial\lambda/\partial H$) occurs in fields ∼80 Oe, corresponding to the maximum of the ME voltage in Fig. 2a.

4. Nonlinear magnetoelectric effect

With an increase in the amplitude of the excitation field h, a nonlinear ME effect, the generation of voltage harmonics due to nonlinearity of magnetostriction, was observed in the Ni-PZT structure [16,18]. Fig. 3 shows the frequency spectrum of the signal generated by the described structure, measured at an excitation field with h = 30 Oe, frequency f = 120 Hz, and bias field H = 30 Oe. In addition to the fundamental harmonic u_1, the second u_2, third u_3, and higher harmonics also appeared in the frequency spectrum. It was shown [16] that the amplitudes of the first and higher harmonics are given by the following relations: $u_1 \sim qh$, $u_2 \sim p{\cdot}h^2$, $u_3 \sim r{\cdot}h^3$, etc., where the coefficients $q = \partial\lambda/\partial H$, $p = \partial^2\lambda/\partial H^2$, and $r = \partial^3\lambda/\partial H^3$ are the corresponding derivatives of magnetostriction λ with respect to the field H. The amplitudes of the odd harmonics u_1 and u_3 for low amplitudes