Magnetoelectric structure with integrated current carrying electrodes

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Abstract. Various methods of magnetoelectric effect excitation in a composite structure consisting of ferromagnetic and piezoelectric layers are investigated and compared, such as: by ac magnetic field of electromagnetic coil, by ac current flowing through external conductive strip, by ac current flowing through the ferromagnetic layer, and by as current flowing through electrode of the piezoelectric layer. It is shown that ac current flowing through the ferromagnetic layer effectively excites both linear and nonlinear magnetoelectric effects due to absence of demagnetization. Specific dependence of the voltage harmonics on the permanent magnetic field under the structure excitation by ac current are observed and explained.

1. Introduction
Magnetoelectric (ME) effect in composite ferro-magnetic (FM) - piezoelectric (PE) structures arises due to combination of the FM layer magnetostriction and piezoelectricity in the PE layer [1]. The effect is usually excited by ac magnetic field generated by a volumetric magnetic coil, which complicates the design and limits the possibility of using planar technologies. It was also shown, that ME structures can be excited by an electric current flowing directly through the FM layer of the structure [2], or by a linear current flowing through a planar strip, placed near the structure surface [3].

In this work we investigated and compared different methods of the linear ME effect excitation in a bilayer ME-PE structure: using uniform ac magnetic field created by a coil, using ac current flowing through an electrode of the PE layer, using ac current flowing directly through the FM layer, and using ac current flowing through a planar conducting strip placed near the structure surface. Specific features of the different ME effect excitation methods are then discussed.

2. Samples and measurements
Schematic view of the FM-PE structure under investigation is shown in figure 1. The PE plate, 33 mm in length and 300 μm thick, was fabricated of lead zirconate titanate (PZT-5) ceramics. Two Ag-electrodes were deposited on the PZT plate surfaces and it was poled normally to the plane. Then, one electrode of the plate was covered with a thin layer of photocurable Mechanic LY-UVH900 polymer. This dielectric layer provided electrical isolation between the PZT plate and the FM layer. The FM layer, 33 mm in length and 20 μm thick, was made of amorphous magnetostrictive alloy FeBSiC (Metglas 2605S) with saturation magnetostriction of 20 ppm. The PZT plate and Metglas layer were bonded together with a cyanacrylate glue. Two structures of different width were fabricated and used in measurements: the wide sample contained 9 mm wide PZT layer and 5 mm wide Metglas layer, the narrow sample contained 3.5 mm wide PZT layer and 1.5 mm wide Metglas layer.
The structure was fixed in its center with a rigid rod and placed in a dc magnetic field $H$ with magnitude up to 120 Oe. The dc field was created by an electromagnet and applied parallel to the long side of the structure.

To excite ME effect with a uniform ac field, we used Helmholtz coils which produced ac field of frequency $f = 42 - 52$ kHz and amplitude $h = 0.25$ Oe, directed in the structure plane and perpendicularly to its long side.

![Figure 1. Schematic view of the FM-PE structure. Excitation current $I$ flows though the Metglas layer.](image)

To excite ME effect with a current, we applied Agilent 33210a generator output voltage $U_g(f)$ directly to the ends of the PZT electrode, to the ends of the Metglas layer (shown in figure 1), or to the ends of the planar Cu-strip, 9 mm wide, placed at the distance 0.5 mm apart from the structure. In all cases the current $I \approx 200$ mA generated ac magnetic field in the FM layer, directed perpendicularly to its long side, and thus excited the ME effect.

The voltage $u$ generated between electrodes of the PZT layer due to ME effect was amplified by a SR560 preamplifier and registered with an AKIP-2401 voltmeter. Nonlinear response of the structure was measured using a SR770 low frequency spectrum analyzer and SR850 lock-in amplifier.

3. Linear magnetoelectric effect

Figure 2 shows measured dependences of the ME voltage $u(f)$ on the frequency $f$ of the excitation field or excitation current for wide sample at $H = 5$ Oe. A peak near the frequency $f_0 \approx 46$ kHz with quality factor $Q \approx 10^2$ appears due to excitation of the main mode of in-plane longitudinal acoustic oscillations of the structure. One can see, that all excitation methods provide approximately the same amplitude of the resonant voltage. However, for the excitation with a current passing through the electrode, the ME signal appears against the background of a strong conductive pickup, which leads to a distortion of the resonant curve and complicates the ME signal extraction.

Figure 3 shows measured magnetic field dependences of the ME voltage $u(H)$, generated by the wide structure at the resonance frequency $f_0$ for all excitation methods. Magnitude of the voltage excited by a current flowing through the electrode is taken as a difference between the minimum and maximum voltages in figure 2.

It is seen, that all considered excitation methods provide qualitatively similar field dependences. The ME voltage $u$ increases with increasing $H$, reaches a maximum at $H_m \approx 5$ Oe, and then gradually goes down due to saturation of the Metglas layer. The field $H_m$ corresponds to the maximum of the piezomagnetic coefficient, where $\lambda(H)$ is the field dependence of the Metglas magnetostriction. The highest ME voltage coefficient for the structure excitation by the coil reached 2 V/(Oe\cdot cm), where $d$ is the thickness of the FM layer. Data of figure 3 let to estimate effective magnetic fields created by current $I = 200$ mA flowing through the electrode, Metglas, or conductive strip. Current through the electrode created field $h_{\text{eff}} \approx 0.17$ Oe, through the Metglas – $h_{\text{eff}} \approx 0.21$ Oe, and through the conducting strip – $h_{\text{eff}} \approx 0.13$ Oe.

Figure 4 shows similar field dependences of ME voltage $u(H)$, measured for the narrow sample, except that for the case of excitation with a conductive strip. Compared to the wide sample, the optimal
bias field \( H_m \) for all excitation methods is shifted down to \(~1.5\) Oe. Under excitation with a current flowing through the Metglas, the narrow sample generated \(11\) mV at resonance frequency \(46\) kHz and \(H_m\). In all other cases the maximal generated voltage was about \(1\) mV. The estimates gave that the current through the electrode created effective excitation field \(h_{\text{eff}} \approx 0.40\) Oe, and current through the Metglas created field \(h_{\text{eff}} \approx 3.6\) Oe.

**Figure 2.** Voltage \(u\) generated by the wide Metglas-PZT structure vs. frequency \(f\) under excitation by: 1 - electromagnetic coil, 2 - current through the electrode, 3 - current through the Metglas layer, 4 - current through the conductive strip.

**Figure 3.** Magnetic field dependences of resonance ME voltage \(u(H)\) for wide sample for different excitation methods: 1 – by the coil, 2 – by current though the lectrode, 3 – by current though the Metglas layer, 4 – by current though the outer strip.

By using resonance curves, we estimated mechanical quality factors \(Q\) for the structures at different \(H\) values. Figure 5 shows dependences of \(Q\) on the bias field \(H\) for three excitation methods, measured for the narrow sample. One can see, that for the coil excitation and excitation by a current flowing through the electrode, \(Q\) reaches minimum of \(~90\) near optimal bias field \(H_m\) and then monotonously grows to about \(~110\) at \(H = 30\) Oe. Under excitation by a current flowing through the Metglas, \(Q\) falls down from \(90\) at \(H = 12\) Oe to \(70\) at \(H = 30\) Oe.

**Figure 4.** Magnetic field dependence of resonance ME voltage \(u(H)\) for narrow sample for different excitation methods: 1 – by coil, 2 – by current through the electrode, 3 – by current through the Metglas layer.

**Figure 5.** Magnetic field dependence of quality factor \(Q(H)\) for narrow sample for different excitation methods: 1 – by coil, 2 – by current through the electrode, 3 – by current through the Metglas layer.

The unusual field behavior of the quality factor with increase in \(H\) when the structure is excited by a current through the Metglas is apparently due to the nonuniform distribution of internal field in the FM layer. The volume of the layer is divided into two parts, in which the excitation fields strength have
opposite directions. This leads to a more complex domain structure at large H in comparison with excitation by a uniform field.

4. Harmonics generation

As shown above, the current through the FM layer in the narrow sample creates ac magnetic field of large amplitude, capable of exciting a nonlinear ME response. Figure 6 shows frequency spectrum of the ME voltage u(f) when excited by a current of I = 200 mA and f = 10 kHz at H = 2 Oe. It is seen, that the structure generates multiple voltage harmonics.

Figure 7 shows field dependences of the resonance-enhanced amplitudes of the 2nd and 4th harmonics of the ME voltage at the resonance frequency f_r = 46 kHz. The 2nd harmonic was excited by ac current 200 mA with frequency f = f_r / 2. The 4th harmonic was excited by ac current 200 mA with frequency f = f_r / 4. It is seen, that amplitude of the 2nd harmonic monotonously decreases from 30 mV at H = 0 to almost zero at H = 20 Oe. Amplitude of the 4th harmonic also initially drops sharply from 5 mV at H = 0 to zero at H = 5 Oe, and then demonstrates some variations at a level below 0.5 mV up to the field H = 20 Oe.

5. Discussion

To explain the measurement results, let us calculate the field created by a current I flowing through a conductor of width a and thickness b. Let the conductor is thin (b << a) and the current density is uniform over its cross section. Using Ampère’s circuital law, one obtains the expression for the tangential field h_x outside the conductor near its surface

\[ h_x = \frac{I}{2a} \]  

(1)

By substituting the dimensions of the structures and I = 200 mA into (1), we find that the current through the electrode of the wide sample and the current through the conductive strip create field h_{e1} = h_{strip} = 0.14 Oe, respectively, while the current through the electrode of the narrow sample creates field h_{e2} = 0.36 Oe. Calculated values are in good agreement with estimates of effective excitation fields. Similarly, current I flowing through a conductor creates tangential field H_x at a distance y from its central plane

\[ h_x(y) = \frac{I}{ab} y \]  

(2)

It follows from (2), that h_x varies linearly over the thickness of the conductor, vanishes at its center at y = 0 and has opposite directions on its surfaces at y = ±b/2. Magnitude of h_x inside the conductor, near its surface at y = ±b/2, can be estimated by the same formula (1).
By substituting dimensions of the Metglas layers and \(I=200\) mA in (1) and dividing result by 2, we get average field amplitude over the thickness of the layer. The fields are \(h_{mg1} = 0.25\) Oe for the wide sample and \(h_{mg2} = 1.66\) Oe for the narrow sample. Thus, current flowing through a narrow Metglas strip produces stronger excitation field than the current flowing through a wide strip, which is fully consistent with the measurement data.

It is seen from figure 7, that the amplitude of the 2nd harmonic excited by a current flowing through the Metglas layer is inversely proportional to magnetic field \(u_2(H) \sim 1/H\). This qualitatively differs from the field dependence of the 2nd harmonic \(u_2(H) \sim \partial^2 \lambda/\partial H^2\) for the case of ME effect excited by electromagnetic coil [3]. In addition, the amplitude of the 2nd harmonic (\(\sim 30\) mV at \(H = 0\) Oe) is three times higher than the amplitude of the 1st harmonic (\(\sim 11\) mV at \(H = 1.5\) Oe). The amplitude of the 4th harmonic is comparable with the amplitude of the 1st harmonic, which was also not observed previously when the structures were excited by electromagnetic coils [3].

Such a difference can be explained by peculiarities of the FM layer magnetization with ac field produced by ac current. Denote the permanent field directed along the long side of the structure as \(H_y\). The ac current \(I\cos(2\pi ft)\) creates ac field in the transverse direction \(h_x = h\cos(2\pi ft)\). In the case of weak field modulation the total field is

\[
|H| = \sqrt{H_x^2 + h_x^2} \approx H_x + \frac{h^2}{4H_x} \cos(4\pi ft) \tag{3}
\]

Thus, the ac component of magnetic field decreases inversely with \(H_x\) and contains the second harmonic. Since the ac magnetostrictive deformation and generated ME voltage \(u\) are proportional to \(H_x\), this fully explains the measurement results. The presence of component with the excitation frequency \(f\) in the measured ME voltage spectrum can be explained by noncollinearity of the magnetization and magnetic field. The latter may be caused by a magnetic anisotropy of the Metglas layer of the structure due to residual elastic stresses [4].

6. Conclusion

Thus, it was shown that ac current flowing through the layers of the FM-PE composite structure effectively excites linear ME effect and leads to generation of ME voltage harmonics. Under structure excitation by the current flowing through an external conductor it is necessary to isolate this conductor from electrodes of the PE layer in order to reduce parasitic signal at the excitation frequency. Excitation of the ME effect by the current flowing through the FM layer is the most effective, especially for narrow structures. This current produces ac magnetic field directly inside the FM layer that allows to get rid of demagnetizing effect and to increase amplitude of ac modulation field. Due to low resistance and inductance of conductors, excitation of ME structures by the current requires less power and provides higher frequencies, compared to the traditional method of ME effect excitation by electromagnetic coils. The described method of ME structures excitation by linear currents can be used to create various devices using planar technology.

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