Field dependence of magnetoelectric effect in the electromechanical resonance region on the Permendur – Quartz – Permendur structures

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Abstract. The results of an experimental study of the field dependences of the magnetoelectric effect on three-layer Permendur-Quartz-Permendur structures in the region of electromechanical resonance are presented. It has been established that at the electromechanical resonance there exists a bias magnetic field region in that an anomalous behavior of the field dependence of the magnetoelectric coefficient are observed. This effect is explained due to the presence of the $\Delta E$ effect in the magnetostrictive material.

1. Introduction

Compositional multiferroics have recently attracted increasing attention of researchers, as evidenced by the growth of publications on this subject [1]. The potential applications of such materials are possible due to the magnetoelectric (ME) effect, which consists in changing the polarization of a substance under the influence of a magnetic field (direct ME effect) and, conversely, in changing the magnetization under the influence of an electric field (converse or inverse ME effect). Due to the presence of the ME effect based on them, it is possible to create devices in which both electric and magnetic fields are controlled simultaneously [2–5]. Recently, a large number of new composite ME materials based on the magnetostrictive and piezoelectric phases have been synthesized. The ME effect is a new property of such materials, or as they say, product properties [6], and arises due to the mechanical interaction of the magnetostrictive and piezoelectric phases of the composite. The main characteristic of the ME effect is the magnetoelectric voltage coefficient (MEVC) $\alpha_E$, which is determined by the ratio:

$$\alpha_E = \frac{<E>}{H},$$

where $<E> = U/\rho t$ is the average electric field strength in the sample, $U$ is the electric voltage arising on the sample under the influence of an alternating magnetic field $H$, $\rho t$ is the thickness of the piezoelectric. According to the theory of the ME effect presented in [6, 7], the MEVC value at the low-frequency region is determined by the expression:
\[ \alpha_E = \frac{p_Y p_d_{31} (m_{q_{11}} + m_{q_{12}})}{\varepsilon_3 \varepsilon_0 (1 - K_p^2 \left( \frac{m_Y m_t}{m_Y m_t + p_Y p_t} \right))} \cdot \frac{m_Y m_t}{m_Y m_t + p_Y p_t}, \]

where \( p_Y, m_Y \) are the Young's modules of the piezoelectric and magnetostrictive phases; \( p_d_{31}, m_{q_{11}}, m_{q_{12}} \) are the piezoelectric and piezomagnetic coefficients; \( p_t, m_t \) are the thickness of the piezoelectric and the magnetostrictive layers; \( \varepsilon_3 \) is permittivity, \( \varepsilon_0 \) is dielectric constant and \( K_p^2 = \frac{p_Y (p_d_{31})^2}{p_\varepsilon_3} \) is the squared coefficient of electromechanical coupling.

Using the fact that \( K_p^2 \ll 1 \), we can rewrite equation (2) in the first approximation in the form

\[ \alpha_E = \frac{p_Y p_d_{31} m_{q_{11}}}{\varepsilon_3 \varepsilon_0} \cdot \frac{m_Y m_t}{m_Y m_t + p_Y p_t}. \]

In equation (3), the piezomagnetic coefficients \( m_{q_{11}} \) and \( m_{q_{12}} \) are defined as follows:

\[ m_{q_{11}}(H_{bias}) = \frac{\delta \lambda_{||}}{\partial H_{1}}\bigg|_{H_{bias}} \quad m_{q_{12}}(H_{bias}) = \frac{\delta \lambda_{\perp}}{\partial H_{1}}\bigg|_{H_{bias}} \]

where \( \lambda_{||} \) and \( \lambda_{\perp} \) are longitudinal and transverse magnetostriction, \( H_{bias} \) is bias magnetic field. In equation (3) terms \( m_{q_{11}} \) and \( m_{q_{12}} \) have a strong dependence on magnetic field and a term \( m_Y \) has a weakly magnetic field dependence. The remaining terms in expression (3) for the MEVC are independent of the bias field. Thus, the field dependence of the MEVC is determined by the dependence of the piezomagnetic modules on the bias field. The field dependence of MEVC is important when creating devices based on the ME effect. Since the ME effect in composites is associated with mechanical vibrations, a peak increase in MEVC occurs in the region of electromechanical resonance [9]. Despite the fact that the main contribution to the dependence of the magnitude of the effect on the magnetic field is made by piezomagnetic coefficients, the dependence of the Young's modulus on the magnetic field or the so-called Delta E effect makes the significant contribution to magnitude of the effect only in the field of electromechanical resonance [10]. Currently, based on the Delta E - effect, highly sensitive magnetic field sensors have been created [11,12]. Studies have shown that the main frequency of electromechanical resonance for a sample in the form of a rectangular plate with planar vibrations is determined by the expression [13]:

\[ f_{res} = \frac{1}{2L} \sqrt{\frac{m_Y^2 m_t^2 + p_Y p_t}{m_p^2 m_t^2 + p_p p_t}}, \]

where \( L \) is the sample length. When the bias field \( H_{bias} \) changes, the Young's modulus of the magnet \( m_Y \), changes too, which leads to a change in the frequency of the electromechanical resonance. This makes it possible to determine the change in the Young's modulus of a magnet from a change in the frequency of electromechanical resonance [14]. In the present work, the influence of the magnetic field on the MEVC value and the Q factor of the structure in the region of electromechanical resonance are analyzed.

2. Samples and Methodology

The objects of research were the layered structures of permendur – quartz – permendur in the form of rectangular plates 20.0 × 4.5 mm in size. The schematic drawing of the structure is presented on figure 1.
A quartz plate (X-cut) with a thickness of $t_1=0.5$ mm was used in a piezoelectric, and two rectangular permendur plates with a thickness of $t_2=0.16$ mm each were used as a magnetostrictive material. Epoxy adhesive was used as a mechanical connection between layers. The thickness of the polymer layer in the obtained samples did not exceed 5 $\mu$m. The ME effect was studied by detecting an alternating voltage on a sample when it was placed in a bias field and an alternating magnetic field directed along the long side of the sample.

### 3. Results and Discussion

The results of studies of the field dependence of the ME coefficient at a frequency of 1 kHz are presented in figure 2. The field dependence of the ME coefficient has a typical form for magnetostrictive-piezoelectric composite materials. The maximum magnitude of the ME coefficient was $1.9 \text{ V/A}$ with a bias field $H_{bias} \approx 10 \text{ kA/m}$. A study of the frequency dependences of the ME effect showed that they have a pronounced resonance, whose amplitude and frequency change with a change of the bias field. Figure 3 shows the frequency dependence of the ME coefficient in the magnetization field corresponding to the maximum of the effect. The resonance was observed at a frequency of 153.37 kHz, the resonance value of MEVC was equal to $920 \text{ V/A}$ at a quality factor $Q = 980$. 

![Figure 1. The schematic drawing of the asymmetric three layered structure.](image1.png)

**Figure 1.** The schematic drawing of the asymmetric three layered structure.

![Figure 2. The field dependence of low frequency MEVC.](image2.png)

**Figure 2.** The field dependence of low frequency MEVC.

![Figure 3. The frequency dependence of MEVC at bias magnetic field $H_{bias}=22 \text{ kA/m}$.](image3.png)

**Figure 3.** The frequency dependence of MEVC at bias magnetic field $H_{bias}=22 \text{ kA/m}$. 
Figure 4 shows the dependence of the resonance frequency on the bias field. As can be seen from figure 4, in fields up to 16 kA/m, the value of the resonance frequency is less than the resonance frequency of the sample at zero magnetic field. This is the region of negative $\Delta E$ effect. In the bias fields above 16 kA/m, at increasing the magnetic field, the resonant frequency increases and reaches saturation at a magnetic field near 100 kA/m. This is the region of the positive $\Delta E$ effect. This is the region of positive $\Delta E$ effect.

**Figure 4** The field dependence of resonance frequency

**Figure 5** The field dependence of Q-factor

Figure 5 shows the dependence of the Q factor on the bias field. In this case, the quality factor was defined as the ratio of the resonant frequency to the width of the resonance line at the level of 0.707. As follows from a comparison of figure 4 and figure 5, the field dependence of the Q factor qualitatively reflects the field dependence of the resonant frequency.

In the region of negative $\Delta E$ effect, the Q factor decreases by more than four times. As is known, the quality factor is determined by losses in the structure. Thus, it can be argued that the processes associated with the negative $\Delta E$-effect are accompanied by an increase in losses in the structure. The dependence of the resonance frequency and the Q factor on the magnetization field leads to the fact that the field dependence of MEVC in the region of electromechanical resonance has significant differences from the field dependence of MEVC outside the resonance region. Figure 6 and figure 7 show the field dependences of MEVC at frequencies $f_1 = 151$ kHz and $f_2 = 155$ kHz, located below ($f_1 < f_{res}$) and above ($f_2 > f_{res}$) the region of resonant frequencies shown in figure 4. In this case, the field dependences have the form characteristic of the low-frequency ME effect, but with a large MEVC value. The maximum signal is observed at the field $H_{bias} \approx 10$ kA/m, while the MEVC value at the maximum is more than 50 times its low-frequency value, reaching $a_1 = 158$ V/A at a frequency $f_1 = 151$ kHz and $a_2 = 98$ V/A at a frequency $f_2 = 155$ kHz against its low-frequency value $a_{low} = 1.9$ V/A at a frequency $f = 1$ kHz. This increase in the coefficient is due to the approach of the frequency to its resonance value and the associated resonant increase in MEVC. A change in MEVC with a change in the magnetization field in this case is due to a change in the piezomagnetic coefficients $m q_{11}$ and $m q_{12}$. The mechanisms associated with a change in the quality factor due to an increase in losses with a negative $\Delta E$ - effect have not yet been manifested, apparently, due to the still small amplitude of the oscillations.

As the frequency approaches its resonance value, the amplitude of the oscillations increases, which leads, on the one hand, to an increase in the magnitude of the effect, and simultaneously to an increase in losses, and, as a result, to a decrease in the Q factor in the magnetic field region of the negative $\Delta E$-effect, which leads to a decrease in MEVC. Figure 8 and Figure 9 show the field dependences of MEVC at a frequency $f_0 = 152.8$ kHz, corresponding to the frequency of electromechanical resonance in the zero bias field and in the mode of continuous tuning to the resonant frequency.
A characteristic feature of these dependencies is the presence of two maxima. This anomalous behavior of the MEVC coefficient is associated with the presence of two mechanisms - a change in the piezomagnetic coefficients due to a change in magnetostriction with a change in the magnetic field, and a change in the quality factor of the system due to the negative \( \Delta E \) effect. Therefore, it can be argued that the presence of two maxima in the field dependence of the MEVC coefficient is a consequence of the field dependence of the piezomagnetic coefficients and quality factor.

4. Conclusion
A change in the Young's modulus of the permendur in a magnetic field leads to a change in the resonance frequency and quality factor of the structure, which is accompanied by an anomalous behavior of the field dependence of the ME effect in the region of electromechanical resonance in the range of magnetic fields corresponding to the presence of a negative \( \Delta E \) effect. Outside the region of
 electromechanical resonance, the field dependences of the ME coefficient have a typical form characteristic of the low-frequency ME effect.

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