Controllable Inductors and Transformers Based On
Ferromagnet-Piezoelectric Heterostructures
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Received January 19, 2021, peer-reviewed January 26, 2021, accepted January 31, 2021

Abstract: The elements of electrical circuits, which inductance L can be tuned electrically (the so-called "inductors"), and transformers are used in modern electronics, radio engineering and low-power energy for galvanic isolation of circuits and converting voltage amplitudes. In this work, new devices of this type have been manufactured and investigated, using the magnetoelectric effect in ferromagnetic-piezoelectric heterostructures. The inductance of the manufactured inductor is tuned by 400% by a control electric field of up to 10 kV/cm applied to the piezoelectric layer of the structure, and by 1000% by an external magnetic field of up to 10 Oe, acting on the structure. The transformer operates in the range of input voltages of 0-8 V, has a power transfer coefficient of 30% and a voltage transformation ratio of 0-14, tunable by a control magnetic field of up to 80 Oe. Methods for calculating the characteristics of magnetoelectric inductor and transformer are described.

Keywords: magnetoelectric effect, transformer, inductor, piezoeffect, magnetostriction

UDC 538.955; 538.956

Acknowledgments: The research was funded by Russian Science Foundation (grant 19-79-10128).

For citation: Leonid Yu Fetisov, Dmitry V. Chashin, Yuri K. Fetisov. Controlled inductors and transformers based on ferromagnet-piezoelectric heterostructures. RENSIT, 2021, 13 (1):27-38. DOI: 10.17725/rensit.2021.13.027.

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acquisition and processing systems [1,2]. Currently, the most common are inductors, consisting of an electromagnetic coil, with a core made of a ferromagnetic material with high magnetic permeability inside. The inductance of the device is shifted by changing the magnetic permeability of the core using an external magnetic field.

Voltage transformers are used for conversion the amplitude of an alternating voltage and the galvanic isolation of elements of electronic circuits with respect to the dc voltage. Currently, compact transformers using the phenomenon of electromagnetic induction [3] and solid-state transformers using the piezoelectric effect [4] are widely used in low-power electronic circuits. However, both types of transformers have several disadvantages. In particular, electromagnetic transformers contain two volumetric coils, which makes them larger and more difficult to manufacture. Piezoelectric transformers have high input and output impedances. Both types of transformers do not allow quick rebuild the voltage transformation ratio.

In this work, the possibilities of creating a new type of inductors and transformers using magnetoelectric effects in ferromagnet-piezoelectric composite structures are demonstrated. It is shown that the characteristics of such devices can be easily controlled using electric and magnetic fields. In the beginning, the designs of some of the devices developed so far are described. Then a magnetoelectric inductor and a transformer of new designs, manufactured in the work, of higher characteristics, including tuning ranges, in comparison with the known ones, are described and investigated in detail.

2. MAGNETOELECTRIC EFFECTS

One of the ways to create controlled electronic devices is to use the so-called "magnetoelectric" (ME) effects in multiferroics. Materials that possess both magnetic and electrical ordering are called multiferroics. These materials include a number of single crystals and artificially created composite materials containing ferromagnetic and ferroelectric components [5].

There are two types of ME effects: the direct ME effect is defined as the appearance (or change) of the electric moment of the sample \( P \) in an external magnetic field \( H \), the inverse ME effect is defined as the appearance (change) of the magnetization of the sample \( M \) in an external electric field \( E \).

The largest ME effect was found in layered composite heterostructures with ferromagnet and piezoelectric (FM-PE) layers. Magnetoelectric effect in such structures arise as a result of a combination of magnetostriction of FM layer and piezoelectricity in PE layer due to mechanical coupling between the layers. When the structure is exposed to an alternating magnetic field \( h(f) \), magnetostriction leads to variable deformation of the FM layer, this deformation is transferred to the PE layer and it generates an alternating electric voltage \( u(f) \) (direct ME effect). When an alternating electric field \( e(f) \) is applied to the PE layer of the structure, it is deformed due to the inverse piezoelectric effect, the deformation is transferred to the FM layer, which, due to the reverse magnetostriction (or the Villari effect), leads to a periodic change in its magnetization \( m(f) \) (reverse ME effect) [6,7].

By applying constant control magnetic or electric fields to the structure, the efficiency of ME conversions can be varied over a wide range. The use of layers made of various FM and PE materials also opens up wide possibilities for controlling the ME effects. Finally, we note that ME effects in composite heterostructures exist at room temperatures, which is extremely important for applications.

3. MAGNETOELECTRIC INDUCTOR

Inductors in which the inductance shift is carried out by a magnetic field due to a change in the magnetic permeability of a ferromagnetic core
are well known and described, for example, in [1]. Shift of inductance by an electric field was recently demonstrated in an inductor containing a ring of MnZn ferrite with a toroidal winding and a plate of lead zirconate titanate (PZT) inside the ring [8]. The inductance shift reached \( \Delta L/L_{\text{min}} = 20\% \) at field \( E = 5 \text{kV/cm} \). In an inductor based on a Metglas/PZT/Metglas planar structure placed inside an electromagnetic coil, a change in inductance by \( \Delta L/L_{\text{min}} = 450\% \) was observed under the action of a field \( E = 12 \text{kV/cm} \) [9]. In [10,11], the characteristics of electrically tunable planar inductors with FM layers made of Metglas, FeGa, MnZn- and NiCo-ferrites and PE layers made of PZT and PMN-PT ceramics were studied. In [12], an inductor based on a structure with layers of NiZn ferrite doped with Ga and PZT is described, which inductance was tuned by both a magnetic and an electric field.

### 3.1 Construction of ME Inductor

The design of the manufactured in the work ME inductor is schematically shown in Fig. 1. The main element of the inductor is a ring made of PE material with its outer surface covered with the FM material. The ring shape of the inductor core allows obtaining high inductance value while maintaining a small size of the device and also it minimizes electromagnetic stray fields in the interference with the surrounding space. The PE ring is made of widely used piezocermics PZT-19 (manufactured by the JSC Research Institute “Elpa”, Russia) and has an outer diameter \( D = 17 \text{ mm} \), thickness \( a_p = 1 \text{ mm} \) and height 5 mm.

The Ag electrodes \( \approx 2 \text{ µm} \) thick each, were deposited both on the outer and inner surfaces of the ring by firing. And the ring was polarized in the radial direction by applying a constant voltage of 600 V to the electrodes at a temperature of 100°C. The piezocermics PZT-19 has a piezoelectric modulus \( d_{31} = -175 \text{ pm/V} \) and density was \( \rho = 7.5 \times 10^3 \text{ kg/m}^3 \). An amorphous magnetic FeBSiC ribbon (Metglas 2605SA1, Metglas Co, USA) with a thickness \( a_m \approx 25 \text{ µm} \), width \( b = 5 \text{ mm} \) and length 55 mm served as an FM layer. Amorphous FM alloy had a saturation inductance \( B_s \approx 1.6 \text{ T} \), maximal magnetic permeability \( \mu \approx 30000 \), saturation magnetostriction \( \lambda_s \approx 27 \times 10^{-6} \) and the resistivity \( \rho_m = 130 \times 10^{-6} \text{ Ohm\cdotcm} \). The FM ribbon was glued to the outer surface of the PE ring using cyanoacrylate adhesive, which ensured the efficient transfer of deformations across the interface. The structure was embedded in a plastic frame with wound toroidal coil, which consisted of \( N = 100 \) turns of wire 0.2 mm in diameter. The active resistance of the coil with the structure inside was \( R = 1.13 \text{ Ohm} \), the inductance was \( L \approx 75 \text{ µH} \), and the capacitance of the structure was \( C = 3.5 \text{ nF} \). The inductance \( L \) and the quality factor \( Q = \frac{2\pi f L}{R} \) were measured by the serial resonance method using an AKTAKOM AM-3026 RLC meter in the frequency range \( f = 20 \text{ Hz} - 5 \text{ MHz} \) with an accuracy of 0.1%. We investigated the change of the inductance \( L \) using constant magnetic \( H \) and electric \( E \) fields. A radial electric field in a PE ring with a strength of \( E = 0-18 \text{kV/cm} \) was created by applying a voltage \( U = 0-18 \text{kV} \) to the ring electrodes from a Stanford Research Systems PS350 high-voltage source. Magnetic field \( H = 0-200 \text{ Oe} \) was created using Helmholtz coils 15 cm in diameter. Two cases were considered: (1) the field is applied along the axis of the ring structure (shown in Fig. 1) and (2) the field is applied in the plane of the structure. Also, the
change of $L$ was investigated using a circular field $H$ created by a direct current $I = 0-200$ mA flowing through an additional toroidal coil wound on a structure.

### 3.2. Inductance Shift by the Electric Field

The tuning of the device inductance by an electric field $E$ was done by applying a DC voltage of up to $U = 1800$ V to the electrodes on the PZT layer. Fig. 2 shows the dependences of $L$ on the frequency $f$ for different values of $E$. The applied field polarity $E > 0$ corresponds to the stretching of the PZT ring due to converse piezoelectric effect. It can be seen, that for all $E$, $L$ decreases monotonically with increasing $f$ and at the constant $f$, $L$ decreases with increasing $E$. In this case, the maximum and minimum $L$ reached $L_{\text{max}} \approx 80 \mu$H and $L_{\text{min}} = 5.5 \mu$H, respectively. The tuning of $L$ by $E$ was observed in the frequency range up to $\sim 10$ kHz. The tuning coefficient of the inductor by the electric field reached $\approx 412$ % (where $L_0$ is the inductance in the absence of magnetic field).

![Fig. 2. Dependences of the inductance $L$ of the ME inductor on the frequency $f$ when at different electric fields $E$.](image)

Fig. 3 shows the dependences of $L$ on the field at a frequency of 300 Hz when the field $E$ changes in a closed cycle with large amplitude or smaller limits. Without the field ($E = 0$) at a starting point “A” the inductance was $L_0 = 76 \mu$H. One can see from Fig. 3a that with increasing $E$ in the positive direction ($E > 0$), $L$ first slowly increases monotonically to $82 \mu$H, then sharply drops at a field $E \approx E_c$ and after that continues to decrease slowly to $L \approx 15 \mu$H as the field increases to $18 \text{ kV/cm}$. During the subsequent decreasing $E$ to zero, the inductance monotonically increases to a value of $L \approx 70 \mu$H. After the change in the field polarity ($E < 0$) and a subsequent increase in the field, the inductance behaves similarly: at first, it increases monotonically, and then at $E \approx -E_c$ it drops abruptly and continues to decrease to $L \approx 15 \mu$H at $18 \text{ kV/cm}$. In the last segment of the curve, when $E$ increases from $-18 \text{ kV/cm}$ to zero, the inductance also monotonically increases to $70 \mu$H. The characteristic fields $E_c \approx \pm 10 \text{ kV/cm}$ correspond to the polarization reversal field of the PZT ring, at which the polarization vector $P$ in the piezoelectric reverses its direction.

It is seen, that at the field amplitudes more than $E_c$, the electrical tuning of the inductor is essentially nonlinear and has a large hysteresis. The hysteresis is much less when $E$ changes within smaller limits and moves only along the lower part of the curve in Fig. 3a, where there is no repolarization of the structure. Nevertheless, even in this case, the

![Fig. 3. Dependence of the structure's inductance $L$ on the field $E$ at 300 Hz (a) when the field cycles with large amplitudes and (b) when $E$ changes within smaller limits ($E > 0$). (c) Inductance tuning coefficient $\gamma$ dependence on the field $E$. $E_c$ is the field of polarization reversal of the PZT ring. Arrows indicate the direction of change in field $E$.](image)
dependence $L(E)$ remains nonlinear. Fig. 3c shows the dependence $\gamma(E)$, obtained using the data in Fig 3a for $E > 0$. The maximum tuning of the inductance by an electric field reached $\gamma = 413\%$ at 300 Hz.

The change in the inductance of the ME inductor under the action of an electric voltage is associated with a change in the permeability of the magnetic layer due to the converse ME effect. The structure’s magnetic permeability $\mu$ depends on $E$ as [13]

$$\mu_r = \chi^2 + 1 = \frac{\mu_0 M_s^2}{2|K_0 + K_\sigma|} + 1,$$  

$$K_\sigma = \frac{3}{2} \lambda_s \sigma,$$

where $\mu_0$ is the magnetic permeability of vacuum, $M_s$ is the saturation magnetization, $K_0$ is the initial anisotropy constant (including both magnetocrystalline and shape anisotropies), $K_\sigma$ is the stress-induced magnetoelastic anisotropy (stress anisotropy), $\lambda_s$ is the saturation magnetostriction, $\sigma$ is the applied stress. Mechanical stresses applied to the magnetic layer are formed as a result of the action of the piezoelectric layer in a ME inductor. Therefore, $\mu_r$ correlates with the electric field applied to the piezoelectric layer, and relation (1) transforms into:

$$\mu_r = \frac{\mu_0 M_s^2}{2K_0 + 3\lambda_s Yd_{\text{eff}} E} + 1,$$  

where $d_{\text{eff}}$ is the effective piezoelectric strain coefficient, $Y$ is the Young’s modulus, $E$ is the electric field, applied to the piezoelectric. Since the change in the linear dimensions of the inductors due to the piezoelectric effect and magnetostriction is small ($< 0.5\%$), and the magnetic permeability $\mu_r$ of the magnetic material is much greater than 1, the change in inductance should be directly proportional to $\mu_r$. In this case the inductance tuning coefficient $\gamma$ is related to the electric field $E$ by the following expression [14]:

$$\gamma = \frac{L_0 - L_E}{L_E} = \frac{3 \lambda_s}{2 K_0} Yd_{\text{eff}} E.$$

3.3. INDUCTANCE SHIFT BY THE MAGNETIC FIELD

Fig. 4 shows the dependences of $L$ of ME inductor on the frequency $f$ when it is magnetized by an external magnetic field $H$ directed along the ring axis. One can see from figure that at any field in the range $H = 0-200$ Oe the inductance $L$ is approximately constant in the low-frequency region, and then decreases monotonically with increasing frequency. The frequency range, in which $L$ is constant, expands from ~0.2 kHz at $H \sim 0$ to ~100 kHz when the field $H$ increased from zero to 200 Oe. However, the absolute value of $L$ decreases with $H$ increasing. The maximum inductance value was $L_{\text{max}} = 77 \mu$H at a frequency of 0.1 kHz. The minimum inductance value was $L_{\text{min}} = 6 \mu$H in the high-frequency region ~5 MHz for all fields. Dependences similar in shape were obtained for two other orientations of the magnetic field: in the plane of the structure and using a circular field. The main difference lies in the range of the applied magnetic field, which for these cases was $H = 0-20$ Oe.

Fig. 5 shows the dependences of the inductance $L$ of the ME inductor and the inductance tuning coefficient $\gamma$ on the magnetic field and on the control current (for the case of a circular magnetic field). The measurements were

![Fig. 4. Dependences of the inductance $L$ on the frequency $f$ when magnetized by the field $H$ along the axis of the structure.](image)
carried out at a frequency of 300 Hz. The values $H < 0$ correspond to the field with reversed direction. It can be seen for all three magnetic field directions, that $L$ does not depend on the direction of the field and decreases monotonically with increasing $H$.

The inductance decreases by a factor of ~8 at a frequency of 300 Hz under the influence of magnetic field in case of the field orientation along the structure axis (Fig. 5a). As follows from Fig. 4, the tuning range of $L$ under the action of the field decreases with increasing frequency. in the low-frequency region, the tuning coefficient of the device inductance in a magnetic field oriented parallel to the axis of the structure was $\gamma \approx 690\%$ with a control field up to $H = 200$ Oe.

In the case of the field orientation in the plane of the structure (Fig. 5b), the inductance $L$ drops to a minimum value in a field $H \approx 20$ Oe, which is ~10 times less than in the previous case. At the frequency of 300 Hz, $L$ decreases by ~11 times under the influence of a magnetic field. The maximum value of $\gamma$ reaches $\approx 1000\%$ at a value of the control current $I = 0.18 A$ ($H = 9$ Oe).

Additional measurements were carried out in order to explain the mechanism of the restructuring of the inductor by the magnetic field. Fig. 6 shows the measured magnetization curve $B(H)$ for a test sample made of a Metglas 2605SA1 ribbon with dimensions 15 mm x 5 mm x 23 μm, magnetized along the long axis. In the same figure, we’ve also plotted field

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**Fig. 5.** Dependence of the $L$ and the tuning inductance coefficient $\gamma$ on the field $H$ (current $I$) when the field is: (a) directed along the axis; (b) directed in the plane; (c) directed along the generatrix of the structure. The measurements were carried out at a frequency of 300 Hz.

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**Fig. 6.** Field dependences of the magnetic induction $B$ for the Metglas test sample and the normalized permeability $\mu/\mu_{\text{max}}$ for: 1 — test sample; 2 — the ring structure magnetized with a circular field; 3 — the ring structure magnetized along the axis.
dependence of the real part of the normalized magnetic permeability \( \mu'(H)/\mu_{\text{max}} \), obtained by numerical differentiation of the \( B(H) \) curve. One can see that in the low field region the permeability is approximately constant and then gradually drops to zero with increasing \( H \). This dependence \( \mu(H) \) that makes it possible to change the inductance using the magnetic field \( H \). For a qualitative explanation of the cases considered above, let us take into account the demagnetization effects.

It is known that in an FM sample of finite dimensions, due to demagnetization, the average field \( H_{\text{in}} \) inside the ferromagnetic is less than the external field \( H \) and is related to it by the relation [15]

\[
H_{\text{in}} \approx \frac{H}{1 + N\chi},
\]

where \( N \) is the demagnetizing factor of the sample along the direction of the field, and \( \chi(H = 0) \) is the initial magnetic susceptibility. For Metglas \( \chi >> 1 \), so we can take \( \chi = \mu(0) \). Thus, demagnetization leads to a scaling of the external magnetic field by the factor of \( 1 + N\mu(0) \).

By measuring the field dependence \( \mu(H) \) for an FM sample with known \( N \) and knowing \( N \) for another sample, it is possible to construct a field dependence \( \mu(H) \) for the second sample. The demagnetizing factors for the FM sample in the form of a rectangular prism were calculated in [16]. The field dependences \( \mu(H) \) calculated using the measured curve \( B(H) \) for the test sample and equation (4) for the FM strip magnetized along the length and along the width are also shown in Fig. 6. We assume that for an FM ring magnetized with a circular magnetic field, the dependences \( \mu(H) \) have a similar form.

Then it follows from Fig. 6 that when the ring structure is magnetized with a circular magnetic field along the generatrix, \( \mu \) decreases, for example, by a factor of 5, in a magnetic field \( H \approx 4 \text{ Oe} \). That is consistent with a 5 times decrease in the inductance \( L \) of the inductor as it is shown in Fig. 5c when the field changes by approximately 4.5 Oe. Magnetic permeability \( \mu \) decreases much more slowly due to the strong demagnetization when the ring structure is magnetized along the axis. Magnetic permeability on curve 3 in Fig. 6 decreases 5 times when the field changes by 150 Oe, which is in a good agreement with a 5 times decrease of \( L \) in Fig. 5c when the field changes by \( \sim 135 \text{ Oe} \).

The magnetic hysteresis of the structures FM layer upon cycle tuning of the inductor by a magnetic field leads to an uncertainty in the set value of \( L \). The coercive force for the amorphous alloy Metglas 2605SA1 was \( H_c \approx 0.2 \text{ Oe} \). The maximum inductance setting error was \( \Delta L/L \approx 0.3\% \) when the structure was magnetized along the axis and \( \Delta L/L \approx 12\% \) when the structure was magnetized with a circular magnetic field created by additional coil.

**Fig. 7** demonstrates the possibility of tuning the inductor simultaneously by the current \( I \) through the control coil (i.e. by the magnetic field \( H \)) and the electric field \( E \) applied to the PZT-ring. In the absence of current at \( E = 0 \), the inductance was \( L \approx 75 \text{ }\mu\text{H} \). The inductance decreases monotonically with increasing current \( I \) and electric field \( E \). Therefore, with an increase in the field \( E \), the tuning range of the inductance by the current narrows.
4. MAGNETOELECTRIC TRANSFORMER

To date, several different designs of ME transformers have been proposed. Models of both step-up \([17-19]\) (operating on the direct ME effect) and step-down transformers \([20-22]\) (operating on the converse ME effect) based on heterostructures with layers of various FM and PE materials have been created and investigated. The possibilities of controlling the voltage transformation ratio using a constant magnetic field \([18,23]\) or a constant electric field \([24]\) applied to the structure have been demonstrated. Methods for calculating the characteristics of ME transformers of various designs are proposed \([25]\).

4.1. CONSTRUCTION OF THE TRANSFORMER

The composite heterostructure and the design of the ME transformer are schematically shown in Fig. 8a and 8b, respectively. The main element of the transformer is a three-layer heterostructure containing a PE layer sandwiched between two FM layers \([26]\). The PE layer with dimensions of 20 mm\(\times\)10 mm and a thickness \(d_p = 2\) mm is made of transformer piezoceramics \(\text{Pb}(\text{Zr},\text{Ti})\text{O}_3\) (PZT-47 type, manufactured by the JSC Research Institute "Elpa", Russia). The piezoceramics has a piezoelectric modulus \(d_{33} = 290\) \(\text{pC/N}\), high electromechanical quality factor \(Q = 900\), an electromechanical coupling coefficient \(k_p = 0.56\), a dielectric loss tangent \(\tan\delta < 0.6\), and the Curie temperature \(T_C = 270^\circ\text{C}\). Ag-electrodes were deposited on the end faces of the PE layer and it was poled in the direction of the long axis. The capacitance between the electrodes of the PE cell was \(C_2 = 66.3\) \(\text{pF}\). Ferromagnetic layers, 20 mm\(\times\)10 mm in size and \(a_m = 0.5\) mm thick each, are made of magnetostrictive nickel ferrite of composition \(\text{Ni}_{0.99}\text{Co}_{0.01}\text{Fe}_2\text{O}_3\). The layers had a saturation induction \(B_S = 0.33\) \(T\), a saturation magnetostriction \(\lambda_S = 26\times10^{-4}\), initial magnetic permeability \(\mu = 51\), a magnetomechanical coupling coefficient \(k_m = 0.2\), and Curie temperature \(T_C = 500^\circ\text{C}\). The layers of piezoceramics and ferrite were coupled under pressure using a cyanoacrylate adhesive.

The structure was placed inside a 20 mm long electromagnetic coil, containing 120 turns of a wire with a thickness of 0.2 mm. The coil generated an alternating magnetic field \(b\) with the variable frequency \(f\). The structure was rigidly fixed in its central transversal plane for the most efficient excitation of the fundamental mode of longitudinal acoustic vibrations. The resistance and inductance of the coil with the structure inside were \(R_1 = 2.3\) \(\Omega\) and \(L = 168\) \(\mu\text{H}\), respectively. A control magnetic field \(H = 0-200\) \(\text{Oe}\) was applied parallel to the long axis of the structure and the axis of the coil using an electromagnet.

During the measurements, the voltage \(U_1\cos(2\pi/f)\) from a generator (Agilent 33210A), with an amplitude \(U_1\) up to 8 \(V\) and a variable frequency \(f = 0-200\) \(\text{kHz}\), was applied to the input coil of the transformer. The output voltage of the transformer \(U_2\) was measured at the load resistance \(R_L\). Both input and output voltages were measured using a voltmeter (AKIP 2401) with an input impedance of more than 10 \(\text{M}\Omega\). The voltage transformation ratio of the

![Fig. 8. Schematic view of (a) the Ni-Co-ferrite-PZT heterostructure and (b) the transformer. The arrows denote directions of magnetic field H, magnetization M, and polarization P.](image-url)
transformer was determined as $K = U_2 / U_1$. To measure the input power $P_1$ of the transformer, a shunt resistor was connected in series with the coil to determine the current $I_1$. The input active power was calculated by the formula $P_1 = U_1^2 I_1 \cos(\varphi)$, where $\varphi$ is the phase shift between voltage and current. The active power in the output circuit was calculated as $P_2 = U_2^2 / R_L$. The transformer characteristics were recorded for the cases when the frequency $f$ and the amplitude $U_1$ of the input voltage, the control magnetic field $H$ and the load resistance $R_L$ were varied.

4.2. Control by the magnetic field

Fig. 9 shows a typical measured amplitude-frequency response of a transformer with an input voltage $U_1 = 1 \, \text{V}$ and a constant magnetic field of $H = 80 \, \text{Oe}$ for the open-circuit condition (at $R_L = \infty$). One resonance peak around the frequency $f_0 \approx 99 \, \text{kHz}$ was observed in the frequency response. The resonance quality factor was estimated from the width of the resonance curve $\delta f$ at a height of $0.7$: $Q = f_0 / \delta f \approx 143$. The voltage transformation ratio at the resonance frequency is $K = U_2 / U_1 = 14.1$. The calculated value of the resonance frequency of the structure was $f_0 \approx 100.4 \, \text{kHz}$, which is in good agreement with the measured value.

The most important feature of the ME transformer, in comparison with electromagnetic and piezoelectric transformers, is the ability to control the voltage transformation ratio using an external magnetic field. Fig. 10 shows the measured dependences of the voltage transformation ratio $K$ on the frequency $f$ of the input voltage with amplitude $1 \, \text{V}$ in the absence of a load resistance. It is seen that an increase in the field $H$ leads to a strong change in the transformation ratio $K$ and a small shift in the resonance frequency $f_0$.

Fig. 11 demonstrates the dependences of the transformation ratio $K$, the resonance frequency $f_0$, and the quality factor of resonance $Q$ on the control magnetic field $H$, derived from the data in Fig. 10. It can be seen that with increasing field, the transformation ratio $K$ increases approximately linearly from zero to a maximum value of $K = 14.1$ in the field $H_m \approx 80 \, \text{Oe}$, and then monotonously declines with a further increase in the field. The resonance frequency $f_0$ grows almost linearly by 0.4% with the increasing magnetic field. The resonance
quality factor decreases from $Q \approx 200$ in the absence of a field to a minimum value of $Q \approx 143$ in the same field $H_m \approx 80$ Oe, and then rises again to $Q \approx 189$ at $H = 200$ Oe.

The capability to control the voltage transformation ratio is caused by the dependence of the magnitude of the direct ME effect in composite structures on a constant field. To confirm this conclusion, the field dependence of magnetostriction $\lambda(H)$ was measured by a strain gauge glued to the surface of the ferrite layer. Then, using the numerical differentiation, the field dependence of the piezomagnetic coefficient $q(H)$ was found. The obtained dependence $q(H)$ is shown in Fig. 11a. For convenience of comparison, the scale along the vertical axis for $q$ is chosen so that the maxima of the dependences $K(H)$ and $q(H)$ visually coincide. It can be seen that the piezomagnetic coefficient $q$ initially linearly increases with increasing field $H$, reaches a maximum at the same characteristic field $H_m \approx 80$ Oe, and then decreases as the ferrite layer is saturated. The shapes of the field dependences $K(H)$ and $q(H)$ agree qualitatively well. The discrepancy between the curves in the region of large fields can be due to the influence of the Poisson’s effect and the inhomogeneity of the magnetic field inside the FM plates due to the demagnetizing fields, which were not taken into account in the calculations.

The dependence of the resonance frequency $f_0$ and the quality factor $Q$ of the structure on the field $H$ (Fig. 11b) is caused by the dependence of the Young’s modulus and the mechanical losses of the ferrite layer on the magnetic field $H$.

Next, the characteristics of the transformer were measured in dependence on the load resistance in the range $R_L = 0-220$ kΩ at optimal bias magnetic field $H_m = 80$ Oe and amplitude of the input voltage $U_1 = 1 V$. Fig. 12 presents the dependences of the transformation ratio $K$, output power $P_2$, frequency $f_0$, and $Q$-factor of resonance on the load resistance $R_L$. It can be seen that the transformation ratio increases monotonically from zero to 14.1 with the load resistance increasing up to $R_L = 220$ kΩ. In this case, the output power $P_2$ varies non-monotonically: first it increases from zero and reaches a maximum $P_2 \approx 1.18$ mW with a load resistance of $R_m \approx 18-20$ kΩ, and then monotonously decreases to $P_2 \approx 0.9$ mW with a further increase in resistance to $R_L = 220$ kΩ. With an output voltage $U_2 = 50$ V, it was 125 mW.

The resonance frequency $f_0$ monotonously increases by less than 0.5%, from 98.54 kHz to 99.02 kHz with the increasing load. The resonance quality factor $Q$ first steeply decreases with the increasing load resistance from $Q \approx 100$ to $Q \approx 80$ at $R_L \approx 5$ kΩ, and then again increases to $Q \approx 142$ at high load resistances (see Fig. 11b).

Fig. 13 shows the dependence of the ME transformer output voltage on its input voltage at different load resistances. It can be seen that in the investigated input voltage range of 0-8 V the dependences are linear and the range of the output voltages of the transformer reaches hundreds of volts.

4.3. Calculation of the Transformer Characteristics

To explain the dependencies shown in Fig. 12a, we write the equation for the current in the output circuit of the transformer

$$I_2 = \frac{U_{me}}{\sqrt{R_2^2 (1/\omega C)^2 + R_L^2}}.$$  \hfill (6)
where $U_{\text{ME}}$ is the amplitude of the voltage in the output circuit induced by the ME effect. At the resonance frequency the measured active resistance and capacity of the PZT layer were $R_2 \approx 17 \, \text{k}\Omega$ and $C \approx 66.3 \, \text{pF}$, i.e. the condition $R_2 << 1/(\omega C)$ fulfilled, where $\omega = 2\pi f$. Then for the output voltage we get

$$U_2 = I_2 R_L = \frac{U_{\text{ME}} R_L}{\sqrt{R_2^2 + R_L^2}}.$$  \hspace{1cm} (7)

The dependence $K(R_L) = U_2(R_L)/U_1$ calculated using (6) for the amplitude of the ME voltage $U_{\text{ME}} = 15 \, \text{V}$ is shown in Fig. 12a with a dashed line. It can be seen that the theory describes the dependence of the transformation ratio on the load resistance qualitatively well. For the output power $P_2$, using formula (2) and mention ($R_2^2 << 1/(\omega C)$), we obtain the expression

$$P_2 = I_2^2 R_L = \frac{U_{\text{ME}}^2 R_L}{R_2^2 + R_L^2}.$$  \hspace{1cm} (8)

The power at the transformer output, reaches its maximum value at $R_L \approx R_2 \approx 17.7 \, \text{k}\Omega$. The dependence $P_2(R_L)$ calculated using (7) with the parameter values $U_{\text{ME}} = 15 \, \text{V}$ and $R_2 = 15 \, \text{k}\Omega$ is also shown in Fig. 12a with a dashed line. Thus, the theory qualitatively well describes the dependence of the output power on the load resistance.

6. CONCLUSION

Thus, in this work, an ME inductor with a variable inductance tuning coefficient and an ME transformer with a controlled voltage transformation ratio of new designs were manufactured and investigated.

A unique property of an ME inductor is the ability to tune its inductance using external electric and magnetic fields. The inductance $L$ of the device is tuned within $\sim 65 \, \mu\text{H}$ by electric and magnetic fields. The control magnetic field is minimal $\sim 10 \, \text{Oe}$ when the ring structure is magnetized in the plane or along the generatrix and increases to $\sim 200 \, \text{Oe}$ when the structure is magnetized along the axis due to demagnetization effects. The inductance tuning coefficient was $\sim 400\%$ for electrical and $\sim 1000\%$ for magnetic tuning. The power consumption for magnetic and electrical tuning of the inductor is approximately comparable in magnitude and amounts to $\sim 1$-10 mW. However, electrical tuning does not require additional power to maintain a given inductance.

A unique property of the ME transformer is the change of the voltage transformation ratio by an external magnetic field. The transformer operates in the input voltage range of 0-8 V, the voltage transformation ratio reaches $K = 14.1$ and is shifted from zero to the maximum value when the magnetic field $H$ changes from zero to $80 \, \text{Oe}$. The amplitude of the output voltage is linearly dependent on the input voltage in the input voltage range from zero to 8 V. With an optimal load resistance of 20 kΩ, the maximum power at the transformer output reached 125 mW, while the maximum power transfer coefficient was $\sim 30.5\%$.

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