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High-*Q* Piezoelectric Resonators with a Lateral Electric Field and Their Potential Applications

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Abstract—It is shown for the first time that suppressing parasitic oscillations in a piezoelectric resonator with a lateral electric field by applying a damping coating or by spatially separating the HF electric field source from the resonating plate allows us to achieve record-high *Q* values for parallel and series resonances. The potential to fabricate an array of acoustically decoupled resonators on a single piezoelectric substrate, and to design microdisplacement sensors with temperature compensation, is also demonstrated for the first time.

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INTRODUCTION

In developing and refining different acoustoelectric sensors, researchers have in recent years begun to focus their attention on piezoelectric resonators with lateral electric fields. A number of works on such resonators have already been published [1–24]. It has been shown that commonly used resonators with longitudinal electric fields (Fig. 1a) are ill-suited for inclusion in fluid and chemical sensors, since changes in the electric properties of a couplant or a chemically sensitive film have no effect on the resonator parameters. Resonators with lateral electric fields and electrodes on one side of the plate (Fig. 1b) are free from this drawback.

The main difficulty in constructing such resonators is the suppression of unwanted oscillations, which must be done in order to raise the *Q* factor for an isolated resonance frequency. This is because a nonuniform electric field forms in a piezoelectric when alternating voltage is applied to its electrodes. Normal and lateral field components excite a set of acoustic waves with different polarizations. The principal mode for which a resonator is designed is a wave that propagates in the interelectrode space perpendicular to its surface and is excited by the lateral electric field. There are at least three ways of suppressing other unwanted oscillations. First of all, we can optimize the shape of electrodes and position them accurately, relative to the plate's crystallographic axes [9–20, 23, 24]. Crescent-shaped electrodes were used in the indicated studies. Second, an absorbing layer applied to a certain section of the resonator can suppress parasitic oscillations and produce a clear resonance dependence of the real and imaginary parts of electric impedance/admittance [21, 22, 25]. Third, the source of the electric field can be spatially separated from the resonating piezoelectric plate [26, 27].

The results from examining the last two methods for suppressing parasitic oscillations are reported in this work. The potential to fabricate an array of reso-

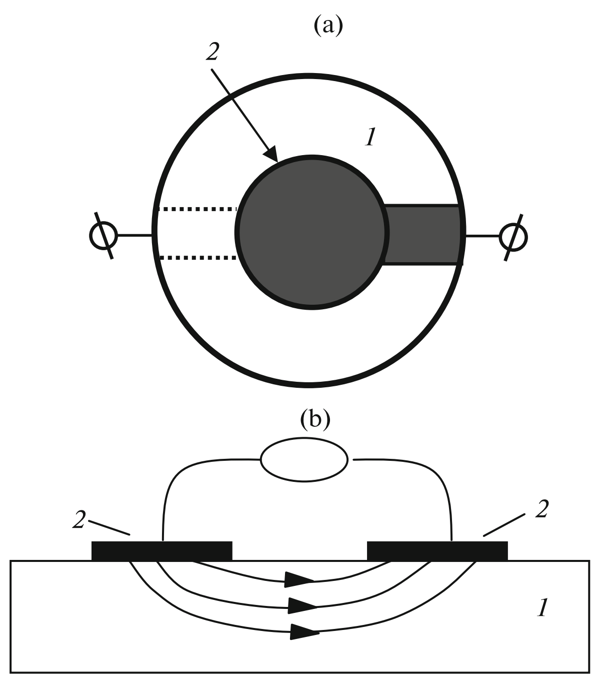

Fig. 1. Schematic diagram of resonators with (a) longitudinal and (b) lateral electric fields. Piezoelectric plate (*1*) and electrodes (*2*) are indicated.

nators with acoustical decoupling better than 50 dB on a single piezoelectric substrate [28, 29] and to design high-sensitivity fluid sensors and microdisplacement sensors [30, 31] is demonstrated. A way of calculating the parameters of such resonators is also developed. The results from these calculations agree with the experimental data [32, 33].

SUPPRESSING PARASITIC OSCILLATIONS BY APPLYING AN ABSORBING LAYER

The effectiveness of suppressing parasitic oscillations with an absorbing coating was demonstrated via the example of an *X*-cut lithium niobate plate 0.5 mm thick. Two aluminum rectangular thin-film electrodes were deposited onto one side of the plate (Fig. 2). The lateral field oriented along the *Y* crystallographic axis excited a longitudinal acoustic wave that resonated between the plate sides. The area around the electrodes was covered with a thin layer of damping lacquer. Frequency dependences of the real and imaginary parts of the electric impedance and admittance of the resonator were measured with an LCR meter (Agilent). A strip of lacquer ~0.3 mm wide was then deposited onto each electrode, and the measurements were repeated. This procedure was repeated until the electrodes were fully coated [21, 22, 25].

As a result, the ranges of varying the interelectrode gap width and the width of the coated area free from parasitic oscillations were determined experimentally. By adjusting the widths of the interelectrode gap and the coated area, we can set acceptable resonator parameters. The classic shape of resonance dependences with no parasitic oscillations is shown in Fig. 3. Measurements of the frequencies of series (f_{ser}) and parallel (f_{par}) resonances allowed us to determine effective electromechanical coupling factor K^2 as [34]

$$K^2 = (\pi/2)^2(f_{par} - f_{ser})/f_{par}. \quad (1)$$

It turns out that K^2 depends not only on the corresponding material constants, but on the wave aperture as well.

The distribution of mechanical displacements in the plate, and the distribution of electric potential in it and the surrounding vacuum, were determined using the finite-element method [32, 33]. It was found that acoustic oscillations of the maximum amplitude corresponding to a longitudinal acoustic wave were localized within the interelectrode gap. The assumed excitation of Lamb waves, which propagate in both directions from the interelectrode gap and are absorbed in passing through the absorbing coating, was confirmed. The frequency dependences of the electric impedance of the resonator were also calculated. These dependences agreed with the experimental data in [32, 33] (Fig. 4).

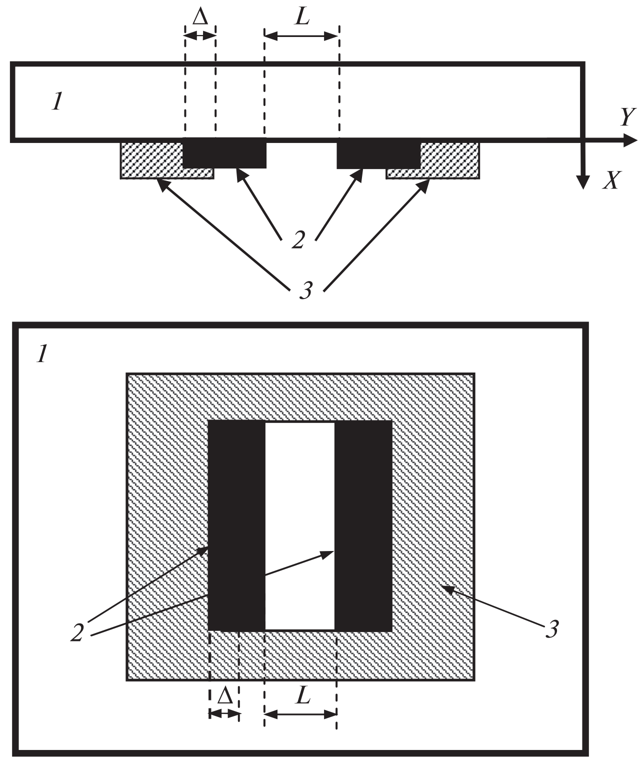

Fig. 2. Schematic diagram of a resonator with a lateral electric field and absorbing coating. Piezoelectric plate (*1*), electrodes (*2*), absorbing coating (*3*), width Δ of the coated part of electrodes, and interelectrode gap *L* are indicated.

INFLUENCE OF THE PIEZOELECTRIC EFFECT ON THE BULK ACOUSTIC WAVE VELOCITY WITH TRANSVERSE ELECTRIC POLARIZATION

An acoustic wave in a resonator with a lateral electric field is transversely piezoactive; i.e., it has finite transverse electric polarization. With an infinite aperture, this wave has no transverse electric field, and the wave velocity is not altered when the piezoelectric effect is switched off [35]. With a finite aperture, however, the finite electric polarization induces an accompanying electric field and a corresponding increase in the wave velocity. The amplitude of this increase depends not only on the formal electromechanical coupling factor, but also on the wave aperture [21].

It was found experimentally that stable resonance is achieved with a longitudinal acoustic wave propagating along the normal to an *X*-cut lithium niobate plate and excited by the transverse components of field *E* that are parallel either to axis *Y* or to axis *Z*. These waves are excited due to the presence of piezoconstants $e_{21} = -2.42$ K/m^2 ($E \parallel Y$) or $e_{31} = 0.3$ K/m^2 ($E \parallel Z$) [21]. In accordance with the Christoffel–Bechmann formalism [7], these waves are invariably transversely piezoactive. It turns out that if the interelectrode gap

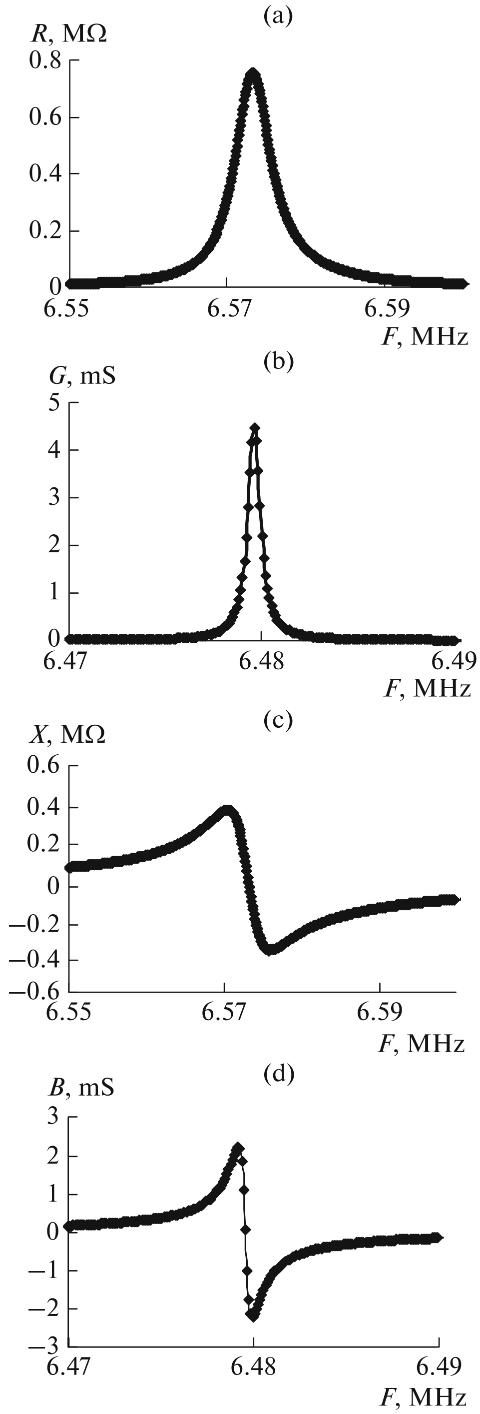

Fig. 3. Frequency dependences of (a, b) real and (c, d) imaginary parts of (a, c) impedance and (b, d) admittance of a resonator with no parasitic oscillations. The Q values of parallel and series resonances are 2000 and 13000, respectively.

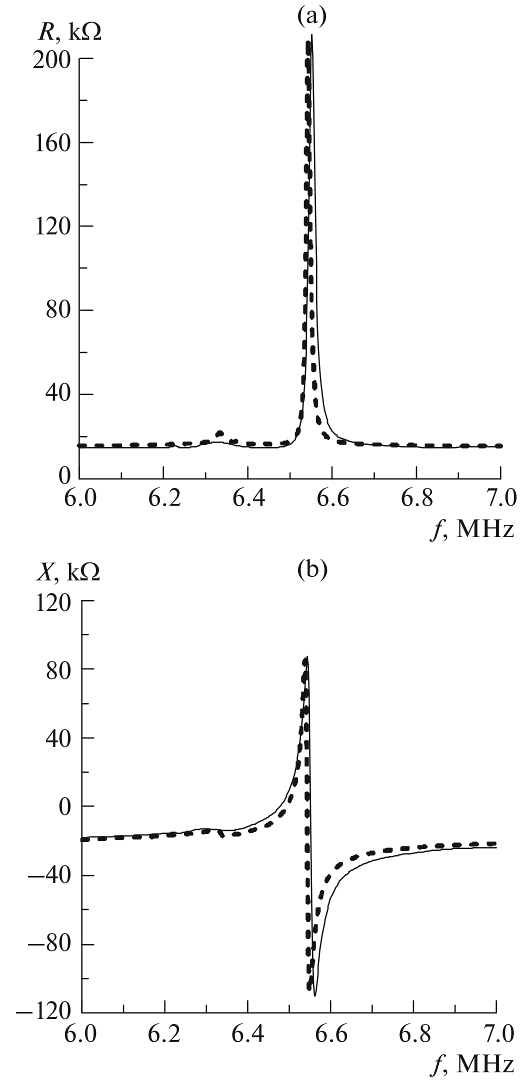

Fig. 4. Theoretical (solid curve) and experimental (dashed curve) dependences of real and imaginary parts of impedance of a resonator with interelectrode gap $L = 1$ mm.

widths are identical, the resonance frequency and the wave velocity for the $E \parallel Z$ orientation are always lower than those for the $E \parallel Y$ orientation. This discrepancy can be attributed to the difference between the orientations of the medium's electric polarization that accompanies the wave and the difference between the formal electromechanical coupling factors, which take values of 7.3% ($E \parallel Y$) and 0.195% ($E \parallel Z$). It was assumed that the velocity of a wave (allowing for its finite aperture) for two electric polarization orientations can be expressed as [21]

$$V_Y = \sqrt{c_{11}/\rho}\left[1 + K^2(Y)A/2\right], \tag{2}$$

$$V_Z = \sqrt{c_{11}/\rho}\left[1 + K^2(Z)A/2\right]. \tag{3}$$

Here, c_{11} is a component of the elastic modulus tensor; ρ is density; and A is an empirical coefficient related to the wave aperture, which is determined by the interelectrode gap. It is evident that $A = 0$ for an

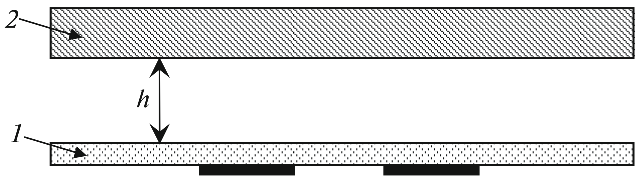

Fig. 5. Schematic diagram of a device incorporating a piezoelectric resonator with a lateral electric field (*1*) and a conducting plate (*2*) located at distance *h* from the resonator.

infinite aperture. The following relation was derived from Eqs. (2) and (3):

$$\frac{V_Y - V_Z}{V_Y} \approx \frac{A\left[K^2(Y) - K^2(Z)\right]}{2}. \quad (4)$$

It was found experimentally that coefficient A varies only slightly in the range of ~0.24–0.27 as the gap width is altered from 1 to 2.5 mm.

INFLUENCE OF ELECTRIC BOUNDARY CONDITIONS NEAR THE CLEAR RESONATOR SIDE ON ITS CHARACTERISTICS

It was demonstrated theoretically (and is physically understandable) that the electric field of the considered resonator extends beyond the boundaries of the piezoelectric plate [32, 33]. Experiments to study the effect the gap between the clear resonator side and the electrically conducting plate has on the frequencies of parallel and series resonances were therefore conducted [30]. A schematic of the experimental device is shown in Fig. 5. The mentioned plate, which was shifted vertically with a special precision mechanism, was positioned above the clear resonator side. Figure 6 shows the dependences of frequencies of parallel (curve *1*) and series (curve *2*) resonances on the width of the gap between the resonator and the conducting plate. It can be seen that the parallel resonance frequency grows along with gap width and reaches saturation. The series resonance frequency is virtually independent of the gap width. It was determined experimentally that the series resonance frequency depended only on temperature. It is evident that this is a sound basis for designing displacement sensors with temperature compensation that can continuously monitor crack growth and deformations of different elements of buildings and bridges, and to measure small relative displacements of pairs of objects.

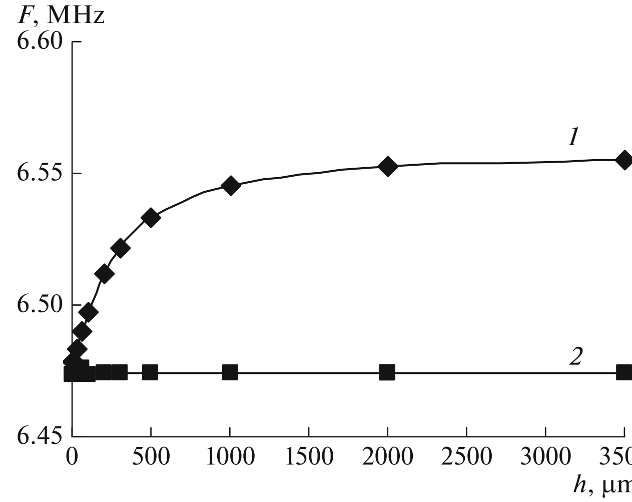

Fig. 6. Dependences of frequencies of parallel (*1*) and series (*2*) resonances on the width of the gap between the clear resonator side and the conducting plate.

SUPPRESSING PARASITIC OSCILLATIONS BY SPATIALLY SEPARATING THE SOURCE OF THE ELECTRIC FIELD AND THE RESONATING PIEZOELECTRIC PLATE

All of the experiments described above were conducted using *X*-cut lithium niobate with a longitudinal acoustic wave. However, transverse waves with no radiation losses are better suited for fluid and biological sensors. Theoretical analysis conducted in accordance with the Christoffel–Bechmann formalism [7] showed that the electromechanical coupling factor for a transverse wave and a 128 *Y–X* lithium niobate plate is 85% if field E is oriented along axis X and is zero for other types of bulk waves.

Similar experiments on fabricating a resonator with a lateral field on a 128 *Y–X* lithium niobate plate with an absorbing coating were performed. However, the resonances were invariably accompanied by parasitic oscillations, precluding the measurement of Q factors.

As noted above, Lamb waves and a bulk wave with polarization are sources of parasitic oscillations. These waves are excited by those components of the electric field under the electrodes that are normal to the plate surface. The structure [26, 27] shown in Fig. 7, which contains two plates, was proposed in order to reduce the influence of these components. Lower glass plate *1* was a support for rectangular electrodes that produced the excitation electric field. The upper 128 *Y–X*-cut lithium niobate plate with no electrodes was positioned near plate *1* with gap d. The transverse electric field in the piezoplate was directed along axis X. The frequency dependences of the real and imaginary parts of electric impedance/admittance were measured at dif-

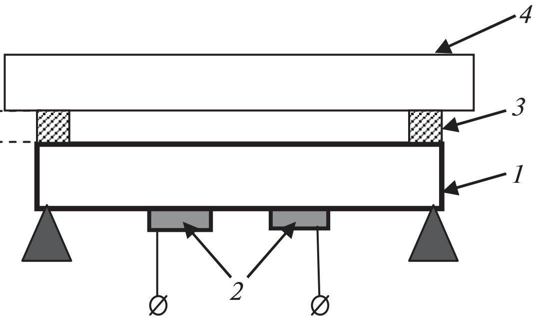

Fig. 7. Schematic diagram of a composite resonator with a lateral electric field. Lower glass plate (*1*), electrodes (*2*) 5×10 mm^2 in size, supports (*3*) to maintain the set gap width, and upper piezoelectric plate (*4*) are indicated.

ferent gap widths. It turned out that the frequency dependences of the real and imaginary parts of electric impedance at gap widths varying from 100 to 500 μm revealed there was parallel resonance with no parasitic oscillations. As for series resonance, the frequency dependences of real and imaginary parts of electric admittance were in all cases split apart from a gap width of 100 μm. At the optimum gap width of 100 μm, however, these dependences revealed classic series resonance. Figure 8 shows the above frequency dependences for a gap width of 100 μm. Record-high Q values (~15000) for parallel and series resonances were measured in the process.

CONCLUSIONS

It was demonstrated for the first time that suppressing parasitic oscillations in piezoelectric resonators with a lateral electric field by applying a damping coating, or by spatially separating the HF electric field source and the resonating plate allows us to achieve record-high Q values for parallel and series resonances (~13000). The influence the piezoelectric effect has on the velocity of a bulk acoustic wave with transverse electric polarization was studied experimentally for the first time. The potential to fabricate an array of resonators with acoustic decoupling better than 50 dB on a single piezoelectric substrate, and to design microdisplacement sensors with temperature compensation, was also demonstrated for the first time.

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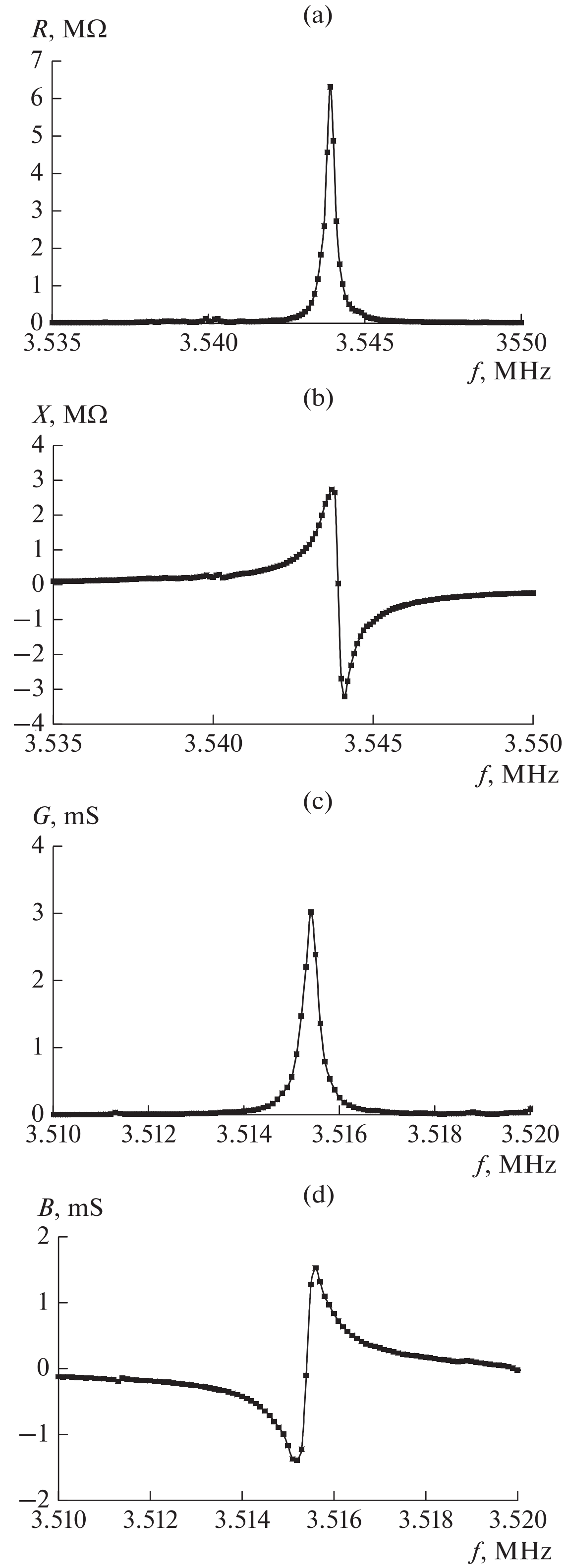

Fig. 8. Frequency dependences of (a, c) real and (b, d) imaginary parts of electric (a, b) impedance and (c, d) admittance of a composite resonator. Gap width h = 100 μm. In both cases, $Q \approx 15000$.

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