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Acoustoelectric effects in reflection of leaky-wave-radiated bulk acoustic waves from piezoelectric crystal-conductive liquid interface

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ABSTRACT

The leaky surface acoustic wave (SAW) propagating along *X*-axis of *Y*-cut lithium tantalate crystal strongly radiates energy in the form of an obliquely propagating narrow bulk acoustic wave (BAW) beam. The reflection of this beam from the crystal–liquid interface has been investigated. The test liquids were solutions of potassium nitrate in distilled water and of lithium chloride in isopropyl alcohol with the conductivity varied by changing the solution concentration. The strong dependences of the reflected wave amplitude and phase on the liquid conductivity were observed and explained by the acoustoelectric interaction in the wave reflection region. The novel configuration of an acoustic sensor for liquid media featuring important advantages of separate measuring and sensing surfaces and rigid structure has been proposed. The application of leaky-SAW radiated bulk waves for identification of different brands of mineral water has been demonstrated.

1. Introduction

Acoustic waves in solids are very sensitive to properties of media adjacent to their propagation or reflection surface, and, therefore, are of great interest for sensing applications. For operation on solid–liquid interface, the waves with shear horizontal (SH) polarization are used, since they allow avoiding considerable loss due to energy radiation into a liquid. These are the bulk waves in the thickness shear mode resonator also referred to as the quartz crystal microbalance (QCM) [1], acoustic plate modes (APM) [2], shear horizontal surface acoustic waves (SH-SAW) [3] and Love waves [4]. A common feature of the latter three wave types is that they are excited and detected by interdigital transducers (IDT) offering much higher frequencies of operation as compared to the thickness-determined frequency of a shear mode resonator, and, consequently, allowing for an essentially higher sensitivity to external perturbations. In the SH-SAW or Love-wave devices, the IDTs are on the same face of the substrate as that exposed to the liquid, and the necessity of transducers protection creates additional technical difficulties. In APM devices, the waves are guided by reflections from opposite surfaces of the substrate, and the IDTs can be fabricated on the face different from that used for sensing. However, to achieve satisfactory separation between multiple modes, the substrates for APM must be sufficiently thin (on the order of several hundred microns); hence, their mechanical fragility is of additional concern. To overcome these drawbacks, we propose a novel configuration of acoustic sensor for liquid media based on interaction of leaky surface and bulk acoustic waves. This is achieved by using leaky surface acoustic waves in *YX*-$LiTaO_3$ that strongly radiate energy into the crystal bulk forming a well-defined obliquely propagating bulk-wave beam [5]. It has been recently shown that the beam reflection from the opposite crystal surface is extremely sensitive to the conductivity of a thin film deposited on the reflecting surface [6]. In the present paper, we investigate the impact of a liquid adjacent to the *YX*-$LiTaO_3$ surface on the reflection of the leaky SAW-radiated bulk wave. We report on the strong dependence of the reflected wave amplitude and phase on the liquid conductivity, which is explained by the acoustoelectric interaction at the reflection spot.

Among various applications of liquid-phase acoustic sensors, those related to the development of artificial tasting and classification systems for food and drink industries are of considerable interest. The employment of acoustic waves for identification of various liquids has been reported [7–10]. In the present paper, we demonstrate the suitability of the leaky-SAW radiated bulk waves for identification of different brands of natural mineral water by the characteristic response of the acoustic wave amplitude and phase.

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2. Experimental technique

The experimental configuration is shown in Fig. 1. The substrate for the acoustic wave propagation was the *Y*-cut $LiTaO_3$ single-crystal plate with thickness 1.64 mm and faces polished flat and parallel. The interdigital transducers (IDTs) for acoustic signal excitation and reception were fabricated from the 0.15 μm-thick aluminum film using a standard photolithography. The center-to-center spacing between the transducers was 6 mm along the crystal *X*-axis. Each IDT had the period Λ = 40 μm (both finger width and spacing being equal to 10 μm) with the number of finger pairs N = 10, and the aperture W = 1.5 mm. The leaky surface acoustic wave (LSAW) was excited by the transmitting IDT. In *YX*-$LiTaO_3$, the LSAW strongly radiates energy in the form of a narrow bulk-wave acoustic beam propagating into crystal bulk at the angle of 30° with respect to the substrate surface [11]. Since the leaky SAW loses its energy very fast and evanesces close beyond the IDT limits, the radiation area is confined within the IDT length. After reflection from the opposite surface of the substrate, the acoustic beam travels back and hits the receiving transducer.

The signal transmission between two IDTs was measured using the radio-frequency network analyzer HP 8752A. The wave reflection both from free and metalized surface of the crystal was investigated. In the latter case, the wave reflection area was coated with the thermally evaporated thin (~0.2 μm) copper film. The reflection spot could be easily located by placing a distilled water droplet in different positions on the surface to get the largest decrease in the transmitted signal amplitude.

The test liquids were potassium nitrate (KNO_3) solution in distilled water, lithium chloride ($LiCl{\cdot}H_2O$) in isopropyl alcohol (C_3H_8O, Sigma-Aldrich), and various brands of natural mineral water. The electric impedances of liquids were measured with an LCR meter at 1 MHz frequency by immersing two rectangular $30 \times 20\ mm^2$ metal electrodes with a spacing of 5 mm. By varying the solution concentration, its conductivity was changed in a wide range, whereas the small changes in dielectric constant could be neglected.

3. Results and discussion

3.1. Acoustic wave transmission

Fig. 2 shows the dependence of the transmission loss on frequency for the free reflecting surface without any liquid. The transmission between 40 μm-period IDTs attains maximum at the frequency 99 MHz corresponding to excitation of the leaky surface acoustic wave with velocity 3960 m/s, and the smaller maximum at 80 MHz corresponds to the Rayleigh wave with velocity 3160 m/s. The smallest maximum in between at 86.5 MHz corresponds to the shear bulk wave with velocity 3460 m/s. All these velocity values are in good agreement with literature data [12]. The described below experiments have been performed at the leaky SAW excitation frequency 89 MHz. More detailed calculations of the radiated bulk wave properties could be performed by using software [13] but they are out of the scope of the present paper.

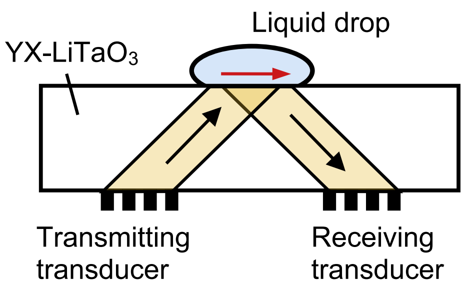

Fig. 1. Experimental configuration. The oblique arrows indicate the incident and reflected bulk waves, respectively, and the horizontal arrow indicates a surface wave excited in the reflection area.

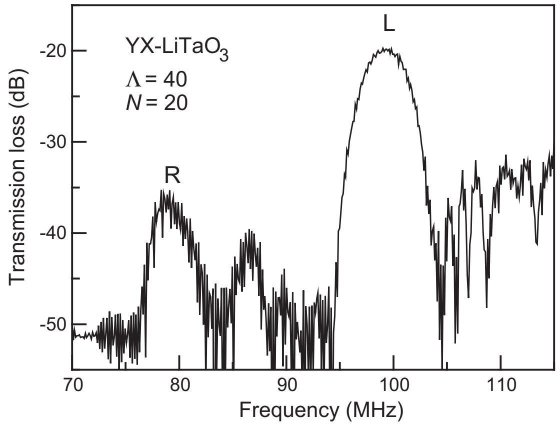

Fig. 2. Acoustic wave transmission vs. frequency in the structure shown in Fig. 1. Peaks *R* and *L* correspond to the Rayleigh and leaky surface acoustic waves, respectively.

3.2. Response to liquid drop deposition

The impact of solution concentration on the acoustic wave transmission is demonstrated in Fig. 3. A droplet of distilled water was deposited onto the wave reflection area on the free $LiTaO_3$ surface, and a small grain of KNO_3 salt was inserted into this drop. The evolution in time of transmitted acoustic wave amplitude and phase was recorded as the salt was gradually dissolving in water. As seen, the amplitude passes a minimum, and the phase monotonically decreases with time. We attribute these variations to the acoustoelectric interaction at the crystal–liquid interface due to increasing liquid conductivity as the dissolution progresses.

The experiments were repeated many times with good reproducibility indicating that possible variations in droplet size were not critical.

3.3. Theoretical approach

For the surface acoustic wave propagating at the interface of piezoelectric solid and conductive liquid, the acoustoelectric atten-

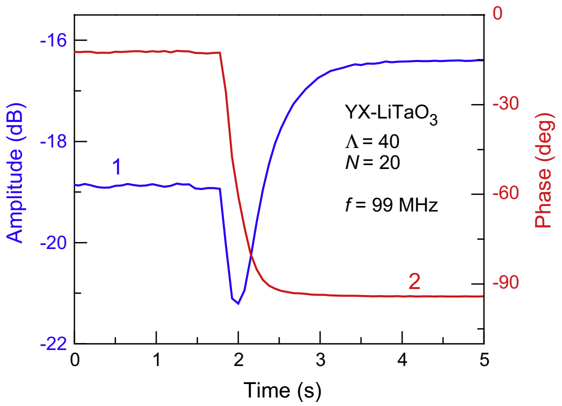

Fig. 3. Time variations in transmitted wave amplitude (1) and phase (2) as a small amount of KNO_3 was dissolving in pre-deposited droplet of distilled water.