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Ultrasonic visualization of inhomogeneities in the structure of shear wave radiators

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It has been experimentally shown that inhomogeneities in the structure of shear wave radiators may be visualized by converting shear vibrations into longitudinal waves on these inhomogeneities. The generated longitudinal waves propagate into the immersion liquid surrounding the radiator and are received by a scanning ultrasonic transducer.

Keywords: shear waves, piezoelectric transducer, ultrasound imaging, acoustic microscope.

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Piezoelectric radiators are widely used in various devices, such as biomedical diagnostic and therapeutic devices, acousto-optic components, and non-destructive testing devices. Their important parameters and characteristics depend on the presence of structure distortions. As typical defects, delamination between the piezoelectric material, substrate and electrodes occurring mainly due to low interlayer adhesion may be regarded. Such inhomogeneities as wafer and substrate cracks should be considered critical. Their most probable sources are mechanical and thermal strains. Defects induce a decrease in the radiator efficiency and undesirable disturbances of the generated field; they also evidence the production procedure violations which reduce the reliability.

The radiator's performance may be assessed by its electrical impedance [1,2]. More informative methods seem to be those that allow measuring the field of a longitudinal-wave radiator with a scanning hydrophone [3] or focused ultrasonic receiver [4]. Distribution of the radiator surface vibrations may be obtained by reconstructing the acoustic hologram recorded by the hydrophone in the immersion fluid [3] or using a laser vibrometer [5]. However, these methods are not applicable to shear wave radiators, since their vibrations are directed along the surface and the normal displacement component is absent. Visualization of the longitudinal-wave radiator structure was performed in the acoustic microscope echo-pulse mode by irradiating the radiator with a focused wave and receiving the wave reflected from it [5,6]. Moreover, it was shown [6] that the emissivity spatial distribution may be obtained by using a scanning focused receiver that receives the wave radiated into the immersion fluid by the piezoelectric transducer under study. This method is not applicable for the homogeneous shear-wave radiator, since it cannot excite longitudinal waves in liquids. However, if the transducer contains inhomogeneities, shear vibrations on them may be transformed into vibrations with a non-zero normal component. In this paper, we propose a method for visualizing inhomogeneities in the shear-wave radiator by detecting longitudinal waves generated by the radiator structure inhomogeneities and propagating towards the receiver through the immersion liquid.

Schematic diagram of the experimental setup is shown in Fig. 1. In this study, we used an ultrasonic shear wave radiator in the form of a wafer *1* made of X-cut lithium niobate single crystal located on a paratellurite acoustic duct *2*. The radiator's lower electrode *3* designed as an indium layer approximately $2\,\mu$m thick was used to mechanically attach the wafer to the sound duct. The wafer's long side was oriented along the lithium niobate crystallographic direction Y_{+131° and directed along axis x in the figure's frame of reference. The paratellurite direction [110] lied in plane (y, z) at the angle of 6.2° to axis z. Applying an electrical signal to upper electrode *4* initiated shear waves in the radiator and sound duct whose displacement vector was directed along axis x.

The wafer thickness was $27\,\mu$m which corresponded to the transducer's antiresonance frequency of about 90 MHz.

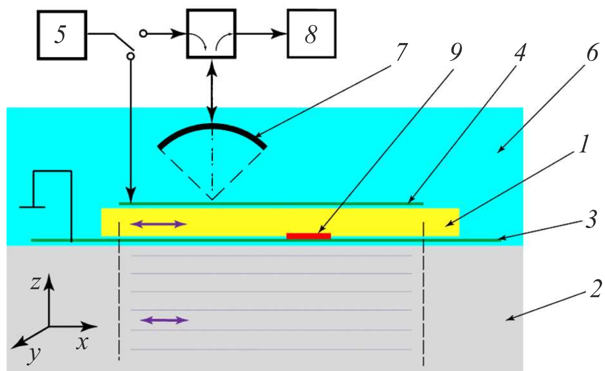

Figure 1. Schematic diagram of the experiment. *1* — radiator (lithium niobate), *2* — sound conductor (paratellurite), *3* — lower electrode, *4* — upper electrode, *5* — pulse generator, *6* — immersion liquid, *7* — focusing transducer, *8* — electronic unit, *9* — inhomogeneity.

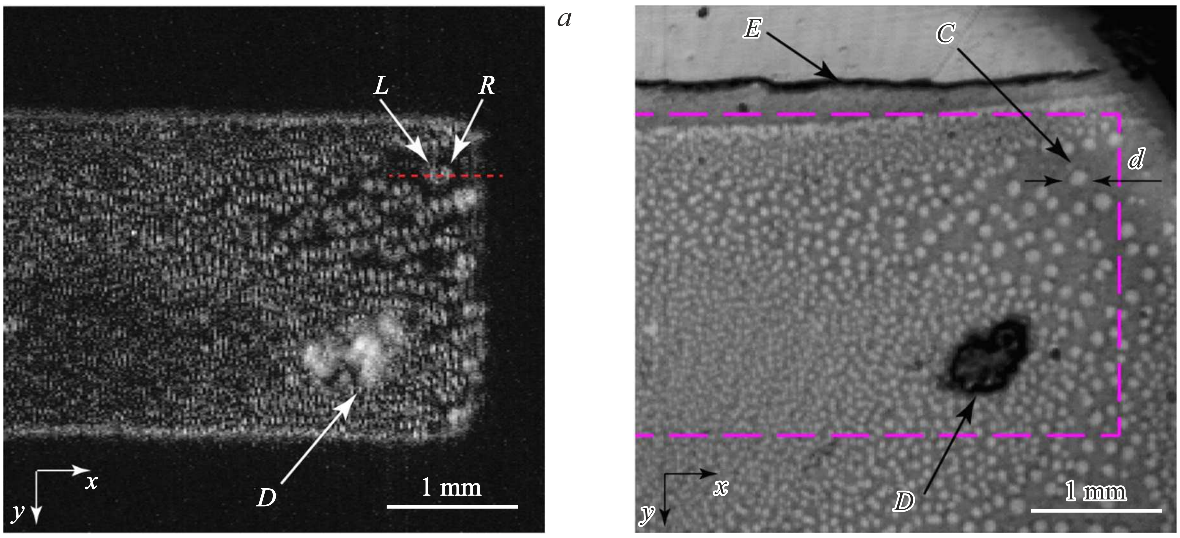

Figure 2. *a* — amplitude of emitted signal $g(x, y)$; *b* — radiator ultrasound image $r(x, y)$: *C* — inhomogeneity; *d* — inhomogeneity *C* size; *L*, *R* — responses emitted by inhomogeneity *C*; *D* — surface defect; *E* — piezoelectric wafer edge.

The matching circuit at the radiator input enabled obtaining the operating frequency band of about 60–100 MHz. In this frequency band, the transducer was excited by video pulses about 5 ns long produced by generator *5*. The radiator was in contact with immersion liquid *6* which was deionized water. Longitudinal waves that may arise from the transformation of shear vibrations in the region of radiator inhomogeneities propagated in water and were received by focusing ultrasonic transducer *7*. The transducer's central frequency and relative bandwidth were 75 MHz and 65 %, respectively, which ensured efficient reception of the radiated pulse waves. The pulsed operating mode allowed extraction in the time domain of the useful signal against the background interference generated by the probing ultrasonic pulse and its re-reflections. After amplification, filtering and analog-to-digital conversion in the electronic unit *8*, the received signals were fed to the computer. Transducer *7* was focused on the radiator *1* surface, which provided transverse spatial resolution of $\sim 20\,\mu$m. The ultrasound absorption coefficient in water at the frequency of 100 MHz was 2.2 dB/mm, while the wave path in liquid was equal to the transducer focal length (3.4 mm). Thus, the signal attenuation in liquid did not exceed 7.5 dB and did not critically affect the method sensitivity. To measure the spatial distribution of received responses $g(x, y)$, the transducer was mechanically scanned in plane (x, y).

The described experimental setup was built based on the scanning acoustic microscope; its more detailed description is given in [4]. The ultrasound images of inhomogeneities were constructed in the standard echo-pulse mode of the acoustic microscope. Generator *5* was connected to transducer *7* that emitted probing focused waves and received responses $r(x, y)$ reflected from the object.

Spatial distribution of the transducer-emitted signal $g(x, y)$ amplitude is presented in Fig. 2, *a*. The received responses are located in a well-defined region corresponding to upper electrode *4* (Fig. 1). The width of this region is equal to the electrode width (2.4 mm). The responses have different shapes and sizes and are unevenly distributed across the region. Note that inhomogeneities on the entire piezoelectric wafer surface are not visible in the radiator optical images, except for large defect *D*. In the ultrasound $r(x, y)$ image (Fig. 2, *b*) obtained in the echo-pulse mode of the acoustic microscope, defect *D* is also observed, but the upper radiator electrode is invisible because of its low thickness. Its location is shown by the dashed line. Besides large defect *D*, the figure's upper panel demonstrates uneven edge *E* of the lithium niobate wafer, over almost entire surface of which responses from small inhomogeneities are distributed. Temporal structure of the incoming ultrasonic signals shows that those inhomogeneities are located in the vicinity of the wafer-to-sound duct interface (see Fig. 1). Their sizes and positions match those of responses in the $g(x, y)$ image formed by the transformation of shear vibrations (Fig. 2, *a*). It is important to note that only those defects that are located under the electrode contribute to the $g(x, y)$ signal. Thus, signals are generated not over the entire piezoelectric wafer surface but just in the shear wave radiator. As the image of $r(x, y)$ shows (Fig. 2, *b*), the defects are predominantly round in shape. Responses emitted by the piezoelectric wafer (Fig. 2, *a*) also have a rounded outer boundary, but they are divided into two parts. For instance, inhomogeneity *C* in the $r(x, y)$ image corresponds to response $g(x, y)$ exhibiting well-distinguished halves *L* and *R* (Fig. 2, *a*).

Fig. 3, *a* presents the spatial-temporal structure of signal $g(x, t)$ recorded as a function of coordinate x and time t. The signal is recorded along the dashed line (Fig. 2, *a*) passing through the defect. The signal value is represented by shades of gray; the light shade corresponds to the positive

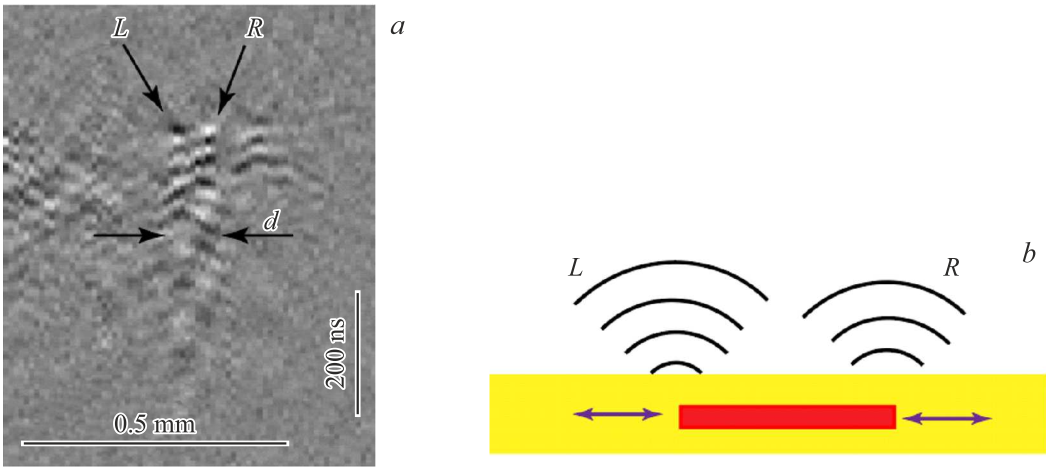

Figure 3. *a* — signal $g(x, t)$ measured in the vicinity of inhomogeneity; *b* — schematic diagram of the longitudinal wave generation in liquid.

signal polarity, while the dark shade represents the negative polarity. The response arrival time corresponds to the time of the longitudinal ultrasonic wave propagation from radiator *1* to receiving transducer *7* (Fig. 1). Response size d is approximately $140\,\mu$m, the vibration period in the received wave packet is about 15 ns, which is consistent with the frequency range of the ultrasonic emitter and receiver. In the received response, components L and R (Fig. 3, a) located above the defect edges are distinguished, while in its center the signal is almost fully absent. It is also important to note that components L and R are opposite in polarity.

Behavioral features of the generated signals may be qualitatively explained as follows (Fig. 3, b). When horizontally polarized shear motions interact in the radiator material with inhomogeneity edges, the tangential deformation field gets distorted and the vertical deformation component arises on the interface between the radiator and immersion liquid. This component gives rise to radiation into liquid of the longitudinal wave which is received by the focusing transducer. Since at any given time moment exciting oscillations at the defect edges are directed oppositely relative to its center, polarities of the L and R responses are also inverted. In addition, the signal generation is low in the vicinity of inhomogeneity passing through its center and extending along axis y perpendicular to shear vibrations.

Thus, it has been experimentally shown that inhomogeneities in the structure of piezoelectric shear wave radiators may be detected and visualized in the immersion measurement scheme by converting shear vibrations into longitudinal waves in liquid. This method may be used to study the properties of shear wave radiators, develop their fabrication procedure, and control their quality. In this work, studies were performed for a lithium niobate radiator mounted on a paratellurite substrate. This structure is often employed in acousto-optic devices; however, the method field of application seems to be wider. What is important is that the visualized inhomogeneities caused distortion of shear vibrations and generation of a longitudinal wave whose amplitude is sufficient to make it detectable. Thus, the method may be applied for various substrate and radiator materials, including piezoceramics, and for various frequency ranges.

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Conflict of interests

The authors declare that they have no conflict of interests.

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