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THE MEASUREMENT OF MECHANICAL AND ELECTRICAL PARAMETERS OF LIQUIDS

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The sensor for the measurement of mechanical and electrical parameters of liquids such as viscosity, density, elasticity constant, permittivity, and electrical conductivity was developed. The sensor is based on the plate of Y-X lithium niobate with thickness 200 micron. There are two input and two output interdigital transducers (IDT) for launching and receiving SH_0 wave and also container for liquid under study on the plate surface. The aluminum film is deposited on the lower side of plate between one pair of transducers. The continuous electromagnetic signal from HF generator is applied on the input IDTs. SH_0 wave passes under the container and transforms into output electromagnetic signal, which follows in vector voltmeter. When the liquid under study is put into container the velocity and attenuation of wave changes that leads to the change in phase and amplitude of output electromagnetic signals. Acoustic wave passing through electrically open channel is reacted to mechanical and electrical parameters of liquid. The wave passing through electrically shorted channel is reacted only to mechanical liquid parameters. The measured values of changes in phase and amplitudes of output signals allow to determine the sought parameters of liquid by using the special calculation program. The developed sensor may be used as the liquid identifier in food and chemistry industries and for time monitoring of various biological reactions.

At present time there exist a great number of papers devoted to problem of propagation of plane inhomogeneous acoustic waves in solid wave-guides of various types contacting with liquids of different kinds. The most general and detailed review of these papers is presented in monograph [1]. From all types of considered waves the most interesting ones are the acoustic waves with shear-horizontal polarization (SH surface acoustic waves (SAW) and SH plate acoustic waves). These waves can propagate in contact with liquid without significant radiation loss concerned with launching the acoustic energy into liquid [1]. It is explained by the fact that the component of mechanical displacement laying in the surface of plate and being normal to the wave vector prevails over other components. Nevertheless the presence of liquid may lead to significant change in velocity as well as in wave attenuation. It is well known that these changes may be caused by such liquid parameters as viscosity, elasticity and density [1] and also permittivity and electrical conductivity for piezoactive waves [1]. The aforementioned properties of SH waves allowed developing the various sensors based on SH SAW as well as on SH plate waves. These sensors are widely used for determination of the quality of food and everyday liquids [2,3], for determination of quantity of solid particles in liquids [4], for measuring the viscosity [1,5,6], conductivity [1,7,8], and for monitoring of biological reactions [1]. At that in known papers SH SAW and SH plate waves in thick compared to wavelength λ plates were only investigated. Bur recent studies of plate acoustic waves in thin in comparison with wavelength piezoelectric plates have shown that these waves have the more electromechanical coupling coefficient [9] and more gravimetric sensitivity [10] in comparison with mentioned above waves. This leads to stronger influence of liquid presence on wave parameters and to more their sensitivity to change in one or another liquid parameter [11]. This fact apparently may lead to increase of measurement accuracy of pointed liquid parameters. Fig.1 and 2 show the dependencies of velocity (a) and attenuation (b) SH_0 acoustic waves in plate of Y-X lithium niobate plate on conductivity of contacted liquid and its viscosity, respectively. One can see that for normalized plate thickness h/λ = 0.1 the change in liquid conductivity from 10^{-4} up to 100 $(\text{Ohm} \times \text{m})^{-1}$ leads to the change in velocity 6% at the frequency 3 MHz. At that the attenuation changes from 0 up to 1.7 dB/λ. As for liquid viscosity its change from 0 to 10000 N×s/m^2 at the same frequency causes the increase in velocity ~5%. In this case the attenuation increases from 0.2 to 2 dB/λ.

It should be noted that aforementioned sensors are used for measurement or monitoring of only one liquid parameter under condition that other parameters are strongly constant. But this condition

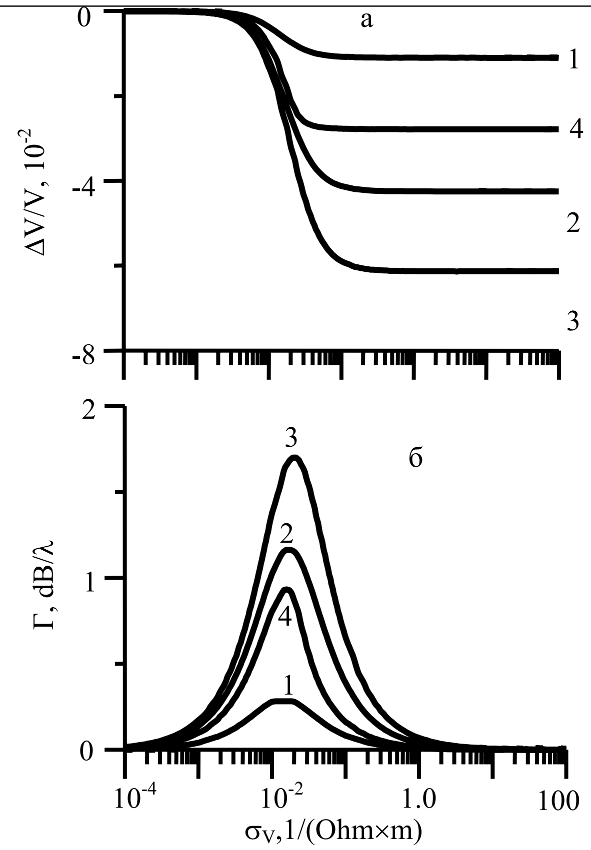

Fig.1. The depedecies of fractional change in velocity $\Delta V/V$ (a) and attenuation Γ (b) of SH_0 wave in Y–X plate of $LiNbO_3$ on liquid conductivity σ_V at frequency f = 3MHz for h/λ = 0.01 (1), 0.05 (2), 0.1 (3), 0.5 (4).

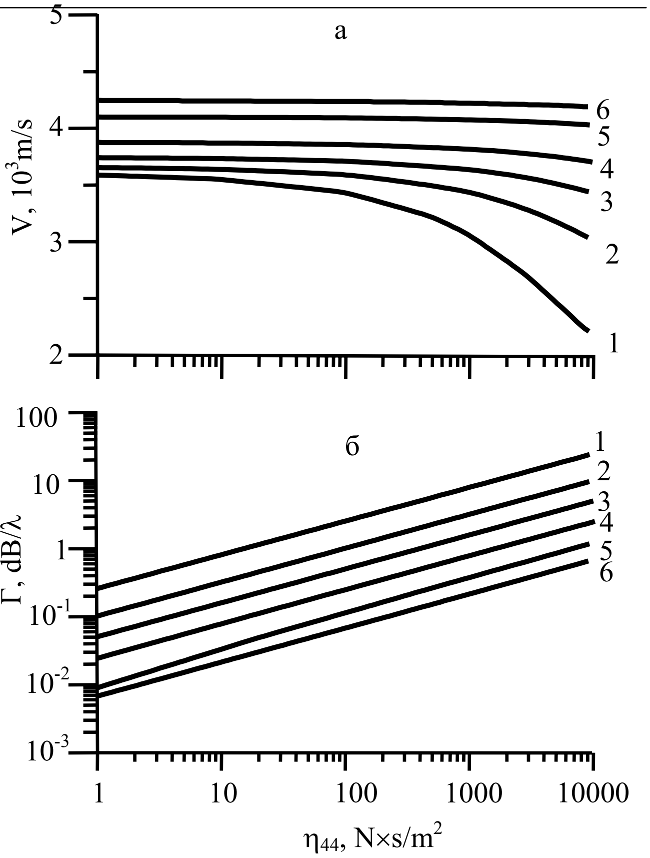

Fig.2. The dependencies of velocity V (a) and attenuation Γ (b) of SH_0 wave in Y–X plate of $LiNbO_3$ on liquid viscosity η_{44} at frequency f = 3MHz for h/λ = 0.01 (1), 0.025 (2), 0.05 (3), 0.1 (4), 0.25 (5) и 0.5 (6).

significantly constricts the field of their applications. For example, the known acoustic meter of viscosity [5] does not allow the measurement of aqueous solution of glycerol and engine oil because they have different not only viscosity but also values of elastic constant and density. This paper is devoted to description of the acoustic sensor, which may be used for simultaneous measuring the mechanical and electrical liquid parameters such as viscosity, density, elastic constant, permittivity, and electrical conductivity [12].

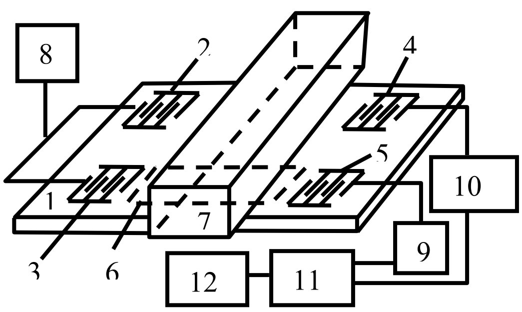

Fig.3. The meter of liquid parameters: 1- plate, 2, 3 – input IDTs, 4, 5 – output IDTs, 6- conducting film, 7- container for liquid, 8-HF generator, 9, 10 – vector voltmeters, 11- ADC, 12 - computer.

The scheme of the acoustic meter is presented in fig. 3. One can see that the sensor of mechanical and electrical liquid parameters is based on the plate of Y-X lithium niobate 1. It means that the normal to this plate and propagation direction of wave are parallel to the axes Y and X, respectively. The first 2 and the second 3 input interdigital transducers (IDT) are set on the upper surface near the one edge of the plate. Near the opposite plate edge there are the first 4 and the second 5 output IDTs. Each transducer has the spatial periodicity 1.3 mm and aperture 12 mm. Thin conducting film 6 is deposited on the lower side of the plate between the second input IDT 3 and the second output IDT 5. The liquid container is placed on the upper side of the plate 1. The length of the container in the direction, which is perpendicular to the wave vector, was chosen enough for covering both acoustic channels. So, one acoustic channel is electrically open whereas the part of another channel is electrically shorted. The first 2 and the second 3 input IDTs were connected with HF generator 8 and the signals from the first 4 and the second 5 output IDTs followed in the vector voltmeters 9 and 10. The output signals from these voltmeters through the analog-to-digital time converter (ADC) 11 entered in computer 12.

The plate thickness h corresponded to the condition h = 0.15λ, which ensures the maximum of electromechanical coupling coefficient [9] and sufficiently high gravimetric sensitivity [10]. The plate thickness ~200 micron was chosen as optimal because such plate has enough mechanical strength for cross sizes 1.5 – 4 cm. From this fact and aforementioned condition h/λ ≈ 0.15 the optimal wavelength turned out to be λ = 1.3 мм, which corresponds to the frequency ~3.5 MHz for SH_0 wave.

The liquid container represents the glass rectangular frame glued to the plate surface by the special glue, which is chemical-resistant for such chemical-aggressive liquids as alkali and organic dissolvent. After drying this glue became the rubber-like material and does not cause significant perturbation in process of wave propagation. Due to this fact the additional insertion loss does not exceed 1 dB.

The measurements were carried out in the following way. The signal from HF generator 8 followed to the first 2 and the second 3 input IDTs, which launched in plate 1 acoustic SH_0 waves propagating to the first 4 and second 5 output IDTs, respectively. Output IDTs 4 and 5 transformed the acoustic oscillations into electromagnetic ones, which followed in vector voltmeters 9 and 10. The measured values of amplitude and phase entered in computer 12 for processing through the analog-to-digital time converter 11. The placing of liquid into container 7 changed the velocity and attenuation of acoustic wave and this leaded to the change in phase and amplitude of corresponding electromagnetic signals. Apparently that acoustic wave passing between input 2 and output 4 IDTs reacted on mechanical as well as electrical properties of liquid because the corresponding space under container was electrically open. The acoustic wave passing between input 3 and output 5 IDTs reacted only on mechanical properties of liquid because the corresponding space under the container was electrically shorted due to the presence of the conducting film 6.

Therefore the meter allows to measure four values, namely two values of the amplitude and two values of the phase of the electromagnetic signals on the outputs of the first and second acoustic channels. These measured values, which were fixed by computer, unambiguously were connected with sought parameters of liquid. In order to find these sought parameters, i.e. elastic constant, density, viscosity, permittivity, and electrical conductivity we made the following. At first we have measured the amplitude and phase at the output of each channel for the presence in container the distillated water, the parameters of which are well - known. Then the aforementioned values were measured in the presence of the liquid under study. By using the measured values of the amplitude and phase at the outputs of each channel, the given values of container length parallel to wave vector and wave frequency we determined the changes in attenuation per wavelength and in velocity for SH_0 wave for metallized and nonmetallized plate in the presence of investigated liquid respectively the distillated water. These values with high accuracy may be calculated for structure “vacuum – piezoelectric plate – semi-infinite liquid” by using the special computer program. At that the initial parameters were elastic, piezoelectric, and dielectric constants of the plate material (lithium niobate), plate thickness ant its crystallographic orientation, and also density, elastic constant, viscosity, permittivity, and electrical conductivity of liquid. We built the criterion function as the sum of squares of differences of measured and calculated values. By enumeration of the liquid parameters in given ranges we determined the minimum of this function and corresponding liquid parameters were considered as sought ones.

As example we measured the parameters of the mixture of glycerol and water solution of sodium chloride. The density, viscosity, permittivity, and electrical conductivity were measured by using other standard methods: density – by analytical balance and measuring glass, viscosity – by dropping viscosimeter, permittivity and electrical conductivity – by plane capacitor filled by liquid and precision LCR meter. The data obtained by standard known and described in the paper methods are presented in Table 1.

Table 1.

Parameter / Measurement method	Density, kg/m^3	Viscosity, Pa · s	Relative permittivity	Electrical conductivity, S/m
Standard known method	$10^3 \pm 5\%$	$7{,}1 \pm 5\%$	$80 \pm 2\%$	$0{,}065 \pm 3\%$
Acoustical sensor	$1{,}01 \cdot 10^3$	$7{,}06 \cdot 10^{-2}$	78,8	0,06

The suggested meter may be used in these conditions where it is necessary to measure or control not only separate liquid parameter but their combination and where the standard methods cannot be used. For example, the viscosity, density, permittivity and electrical conductivity of liquid may be measured by dropping viscosimeter, areometer, and plane capacitor with the known area of plates and distance between them, respectively. However, the standard viscosimeter and areometer may not be used in the cases, when one should carry out the continuous monitoring of liquid parameters in time. These are some biological reactions in liquids following by the change of its physical parameters in time. The suggested meter was tested during investigation of biological reactions in suspension of cells E-coli XL-1 at interaction with specific FAG (corresponding to E-coli XL-1). We have found the time of active interaction of the cells with FAG and the time of the next destruction of these cells. For the compensation of the temperature change in parameters the meter may be supplied by the additional reference sensor with container for reference liqid.

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REFERENCES

1. Ballantine D.S., White R.M., Martin S.J., Ricco A.J., Zellers E.T., Frye G.C., Wohltjen H. Acoastic wave sensors. San Diego: Academic Press. 1997. 436 P.
2. Kondoh J. and Shiokawa S. SH –SAW devices as effective identification systems for liquids // Proc. of IEEE Ultras. Symp. 1994 P.507 – 512.
3. Shiokawa S. and Kondoh J. Surface acoustic wave sensor for liquid phase application // Proc. of IEEE Ultras. Symp. 1999. P.445 – 452.
4. Yamazaki T., Kondoh J. Matsui Y., and Shiokawa S. Estimation of components and concentrations in mixture solutions of electrolytes using a liquid flow system with acoustic wave sensor // Proc. of IEEE Ultras. Symp. 1998. P.505 – 508.
5. Ricco A.J. and Martin S.J. Acoustic wave viscosity sensor // Appl. Phys. Lett. 1987. V.50. N.21. P1474-1476.
6. Anisimkin I.V., Anisimkin V.I. Attenuation of acoustic normal modes in piezoelectric plates loaded by viscous liquids // IEEE Trans. on Ultrason. Ferroel. and Freq. Contr. 2006.V.53. N.8. P. 1487-1492.
7. Neimczyk T.M., Martin S.J., Frye G.C, and Ricco A.J. Acoustoelectric interaction of plate modes with solutions //J. Appl. Phys. 1988. V.64. N.10. P.5002-5008.
8. Josse F., Shana Z.A., Haworth D.T., Live S., and Grunze M. On the use of the Z-X $LiNbO_3$ acoustic plate modes devices as detectors for dilutes electrolytes // Sensors and Actuators B. 1992. V.9. P. 97-112.
9. Kuznetsova I.E., Zaitsev B.D., Joshi S.G., and Borodina I.A. Investigation of acoustic waves in thin plates of lithium niobate and lithium tantalite //IEEE Trans. on Ultrason. Ferroel. and Freq. Contr.2001.V.48.N.1. P. 322-328.
10. Joshi S.G., Zaitsev B.D., Kuznetsova I.E., Kuznetsova A.S. Gravimetric sensitivity of acoustic waves in piezoelectric plates // Journ. of Communicat. Technology and Electronics. 2005. V.50. N6. P.647-651
11. Kuznetsova I.E., Zaitsev B.D., Joshi S.G., and Borodina I.A. Acoustic waves in piezoelectric plates bordered with conducting and viscous liquids // Ultrasonics.2001.V.39. N.1. P. 45-50.
12. Zaitsev B.D., Kuznetsova I.E. Sensor of mechanic and electric parameters of liquid. Patent for useful model №2007147776/22 (052366) on 25.12.2007 (in Russian)