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Nonreciprocal backscattering of millimeter waves by lithium niobate crystals when ultrasonic vibrations are excited in them

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The results of experimental studies of millimeter waves backscattering with a frequency of 33 GHz by lithium niobate crystals using an installation based on a Doppler radar (microwave sensor) are presented. The measurements were carried out when ultrasonic vibrations with a frequency of 50.3 kHz were excited in the crystals and in their absence. It is found that due to elastic ultrasonic vibrations in the crystals, the phase modulation of the reflected wave from the crystal–dielectric–metal system occurs, as a result of which the effect of non-reciprocity of backscattering occurs. Detection of the phase difference between the voltage of the backscattering wave and the voltage of the incident (radiated) wave gave a useful signal level up to 50 dB higher than the noise level of the receiving and transmitting path of the microwave sensor. We established experimentally that the amplitude and frequency of the maximum of the envelope of the backscattering spectral components depends on the angle between the crystal symmetry axes and the vector polarization of the incident electromagnetic wave and on the orientation of the crystal in space. These measurements provide qualitative information about the piezoelectric properties of the crystal material and the presence of elastic waves.

Keywords: Nonreciprocal backscattering, lithium niobate crystals, ultrasonic vibrations, Doppler radar, phase detection.

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In recent years, interest increased in the creation of metaenvironments and their elements with nonreciprocal properties [1–3]. In this regard, a search is underway for new and improvement of known methods to control the parameters of elements included in metaenvironments, when used in the „transmission“ and „reflection“ modes [4–8]. In this paper, we present the experimental results of studying the backscattering of microwaves by lithium niobate crystals in which elastic ultrasonic vibrations are excited. There are different approaches to define the nonreciprocity of backscattering [9]. One of them consists in comparing the elements of the backscattering matrix Sp when the polarization of the emitted radio signal changes from horizontal (H) to vertical (V) [10,11]. Another definition of nonreciprocity is needed for spatially modulated 4D-type systems [12] with the ability to process signals in 3D space and time. The object we are considering also belongs to the 4D type. The received backscattering signals in this case can be compared and the scattering matrix can be formed in the same way as it was done in the papers [11,13], but taking into account that the crystal is exposed to ultrasound. It is proposed to take into account the changing state of the system and compare the reflected signal $U0_{XY}(t)$ from an object not excited by ultrasound and the reflected signal when it is exposed to ultrasound. Here X is the polarization index $Um_{XY}(t)$ of the radiated electromagnetic field (EMF), Y is the index of the parameter characterizing the orientation of the object under study with respect to the polarization vector of the radiated EMF. The variable parameter is the phase shift between the voltages of the incident wave and wave reflected from the crystal, determined using a phase detector, and the recorded signal, i. e. the voltage $Um_{XY}(t)$, proportional to the phase shift. In this case, the orientation of the crystallographic symmetry axes of the crystal with respect to the polarization vector of the incident wave can change. Let us write the backscattering matrix Sp:

$$Sp = \begin{bmatrix} U0_{HY1}(t) & U0_{HY2}(t) \\ Um_{HY1}(t) & Um_{HY2}(t) \end{bmatrix}. \qquad (1)$$

The coefficients included in (1) are defined above, the indices $Y1$, $Y2$ are the values of the angle of rotation of the crystallographic symmetry axes of the crystal with respect to the polarization vector of the emitted EMF.

In the unit used, a signal of horizontal polarization is emitted and received, but the object of study changes its position. Changing the crystal position and the parameters of ultrasonic action makes it possible to obtain a family of Sp backscattering matrices and qualitatively study the parameters of crystals. We consider backscattering to be nonreciprocal if the inequalities $U0_{HY1}(t) \neq Um_{HY1}(t)$ and/or $U0_{HY2}(t) \neq Um_{HY2}(t)$ are observed. The coefficients of the matrix Sp in (1) are real functions of the time t. Applying the Fourier transform to $U0_{HY1}(t), \ldots, Um_{HY2}(t)$, we obtain an estimate of the spectral characteristics of the

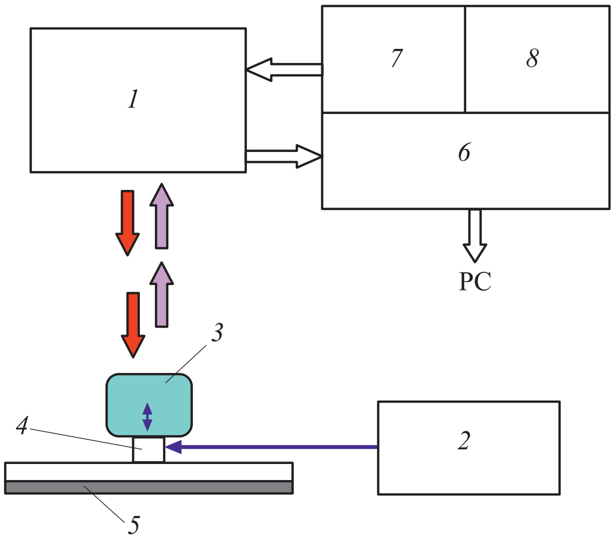

Figure 1. Unit for study of the backscattering of crystals at microwaves when samples are exposed to ultrasonic vibrations. *1* — microwave sensor (Doppler radar), *2* — 50.3 kHz ultrasound generator, *3*— lithium niobate crystal, *4* — piezoelectric transducer MA40E9-1, *5* — reflective screen with a dielectric spacer, *6* — amplifier-converter of the signal from the output of the microwave sensor phase detector with frequency transfer 50.3 kHz to a lower frequency ($\sim$ 9 kHz) and output to PC, *7* — microwave sensor power supply, *8* — sensor setting indicator to maximum sensor sensitivity.

backscattering matrix Sps, in which the Doppler frequencies are the most important. The method of the experimental study of backscattering for solving similar problems was developed earlier [14–17]. In the present paper to study the backscattering of crystals of microwaves at a frequency of 33 GHz under the action of ultrasound, we used unit, the scheme of which is shown in Fig. 1.

The crystal parameters, due to the elastic vibrations excited in them, change with the frequency of the ultrasound generator 50.3 kHz. This is primarily the effective permittivity ε_{eff} of the crystal in the direction of the incident electromagnetic wave. The wave passed through the crystal is reflected from the screen and already in the form of a backward wave again passes through the crystal and is received by the microwave sensor. The change in ε_{eff} for the incident and reflected waves in the crystal leads to an incursion of the phase shift of the wave and a Doppler shift of frequency proportional to the size of the crystal, which depends on its orientation with respect to the front of the electromagnetic wave, as well as on the polarization vector of the emitted EMF. The radiated electromagnetic field has a linear polarization, which was checked using a measuring antenna. The purpose of the experiments was to measure microwave backscattering from crystals upon excitation of elastic ultrasonic vibrations in them. The backscattering of the crystals shown in Fig. 2 were measured.

The crystal in the form of plate (shown by the number *1* in Fig. 2) was installed on piezoelectric transducer *4* (see Fig. 1), fixed on the dielectric gasket 5 mm thick with a relative permittivity ~ 1.5. The crystal was in two positions. In the first one, it was located horizontally and parallel to the polarization vector of the emitted EMF; in the second, the crystal was placed vertically on piezoelectric transducer. The ultrasonic frequency generator was turned on when recording the received signal three times at intervals less than 1 s, the recording time was 10 s. The dependence $U(t)$ was recorded using PC, and then spectral analysis was carried out using standard MathCAD procedures.

The signal $U(t)$ for the horizontal position of the plate is shown in Fig. 3, *a*, for the vertical — in Fig. 3, *b*. The results of the spectral analysis are shown in Fig. 3, *c*. It can be seen that when modulating voltage is applied to the piezoelectric transducer, a pronounced increase in $U(t)$ is observed at both positions of the plate (Fig. 3, *a*, *b*). As expected, the phase modulation of the reflected signal when the plate is mounted vertically is greater than when the plate is placed horizontally. This is explained by the difference in the paths of passage through the plate of the initially incident and then the reflected components of the waves, depending on their position relative to the wave front. After measuring backscattering from the crystals, the effect of reflection from the surface of the piezoelectric transducer was checked. The dependence $U(t)$ was also recorded with a three times voltage supply to the transducer from the ultrasound generator. Visually, $U(t)$ modulation was not observed, which was confirmed by the spectral analysis of the signal. In the process of measuring the backscattering of the grown crystal (shown by the number *2* in Fig. 2), it rotated around the vertical axis Z so that the crystallographic symmetry axes turned out to be at different angles φ with respect to the polarization vector of the emitted transmitting EMI antenna. The measurement was carried out from the cut with the largest area. The frequency dependence of backscattering is shown in Fig. 3, *d*. The measurements were carried out at $\varphi = 0$ and 1.57 rad. According to the measurement data, an expression was written for the Sps

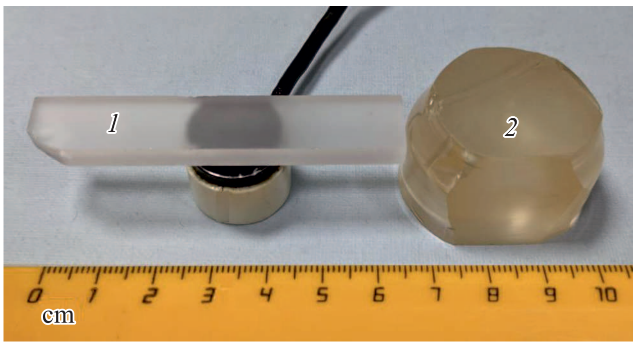

Figure 2. Crystals of lithium niobate. *1* — processed in the form of plate, *2* — grown with the largest cut perpendicular to the *X* axis. The piezoelectric transducer is installed at the bottom.

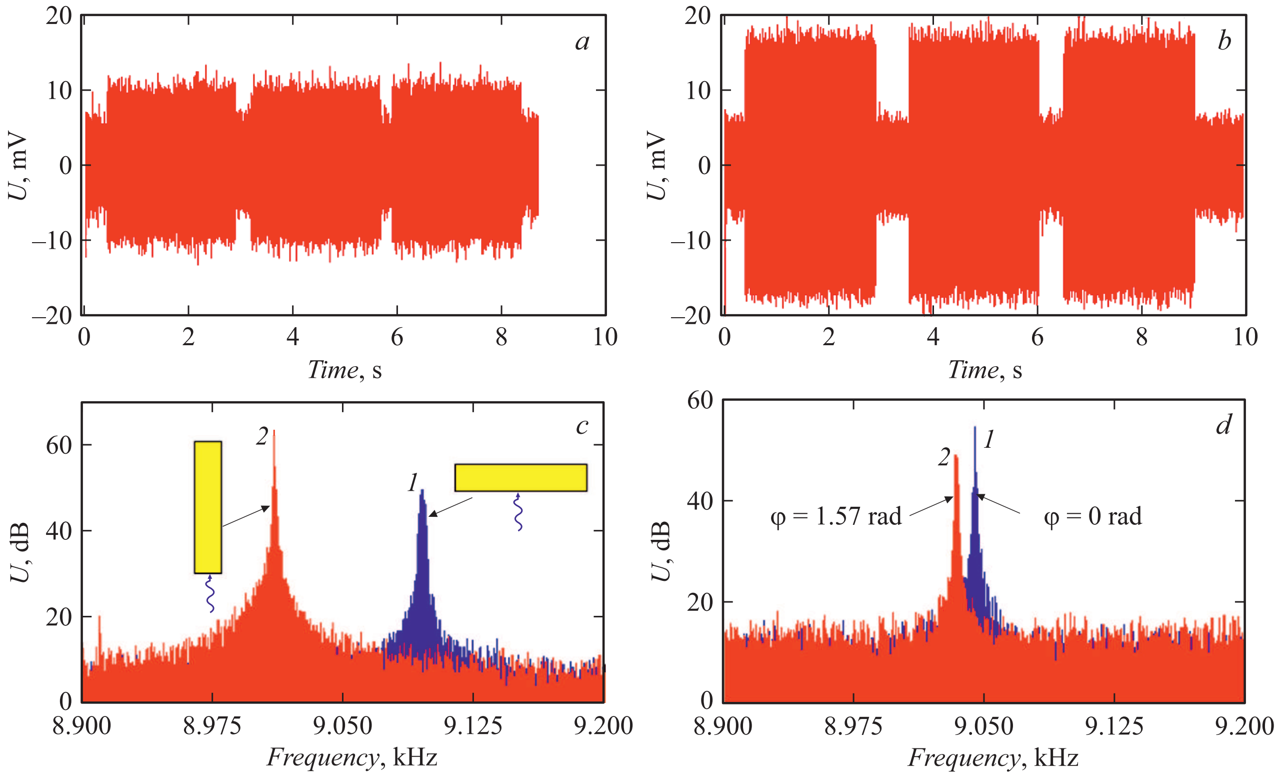

Figure 3. Voltage waveforms at the output of the amplifier-converter when the ultrasonic generator is switched on three times for horizontal (*a*) and vertical (*b*) positions of the plate, spectral characteristics of backscattering from the lithium niobate crystal in the form of plate (*c*) with horizontal (*1*) and vertical (*2*) position of the plate relative to the front of the incident wave and the spectral characteristic of backscattering from the grown crystal (*d*) at angles of rotation of the symmetry axes $\varphi = 0$ (*1*) and 1.57 rad (*2*).

matrix

$$Sps = \begin{bmatrix} U0_{H0}(f) & U0_{H90}(f) \\ Um_{H0}(f) & Um_{H90}(f) \end{bmatrix} = \begin{bmatrix} 7.5888 & 4.6465 \\ 54.684 & 11.482 \end{bmatrix} \Bigg|_{f=9.0442\,\text{kHz}}. \quad (2)$$

The matrix coefficients (2) are indicated on the right side of the expression, they were determined (in dB) at a fixed frequency of 9.0442 kHz. The nonreciprocity manifests itself in the inequality of the coefficients in the columns of the matrix.

To characterize the frequency change of the maximum of the spectral component with the orientation change of the crystal with respect to the polarization vector of the emitted field, the Sps matrix is written in the form of the expression

$$Sps = \begin{bmatrix} \max U0_{H0}(f) & \max U0_{H90}(f) \\ \max Um_{H0}(f) & \max Um_{H90}(f) \end{bmatrix} = \begin{bmatrix} 5.5888 & 0.9096 \\ 54.684 & 48.8430 \end{bmatrix}. \quad (3)$$

In this option, the first column was obtained at the frequency $f = 9.0442$ kHz, the second column corresponds to the frequency $f = 9.0330$ kHz.

The analysis of the graphs (Fig. 3, *d*) shows the dependence of the amplitude envelope of the backscattering spectral components on the angle of rotation of the crystallographic axes φ with respect to the polarization vector of the incident wave. At that the frequency bandwidth change and center frequency shift occur.

Thus, the definition of the scattering matrix for objects with time-dependent parameters was introduced. The presented unit and measurement results illustrate the possibility of experimental study of the backscattering of millimeter waves from lithium niobate crystal when ultrasonic vibrations are excited in it. It is shown that the measurement method based on determining the depth of phase modulation of a wave reflected from a crystal–dielectric–metal system when the elastic vibrations are excited in the crystal provides a sufficiently high sensitivity with the useful signal level exceeding the noise level of the receiving-transmitting path of UHF sensor by up to 50 dB. It was experimentally established that the amplitude and frequency of the maximum of the envelope of the backscattering spectral components depend on the angle of rotation of the crystallographic axes of symmetry of the crystal relative to the polarization of the incident electromagnetic wave in the millimeter range, and on the crystal orientation in space.

The use of the designed unit and modules consisting of lithium niobate crystals and piezoelectric exciters of elastic vibrations in crystals shows the possibility of creating frequency Doppler shift simulators.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.N. Sychev, N.D. Malyutin, Zhurnal radioelektroniki, № 11 (2020). (in Russian) DOI: 10.30898/1684-1719.2020.11.2
[2] S. Taravati, A.A. Kishk, IEEE Microwave Mag., **21** (4), 30 (2020). DOI: 10.1109/MMM.2019.2963606
[3] W.J. Zang, X.T. Wang, A.A. Alvarez-Melcon, J.S. Gomez-Diaz, IEEE Ant. Wireless Prop. Lett., **18** (12), 2661 (2019). DOI: 10.1109/LAWP.2019.2947847
[4] D. Ramaccia, D.I. Sounas, A. Alu, F. Bilotti, A. Toscano, IEEE Ant. Wireless Prop. Lett., **17** (11), 1968 (2018). DOI: 0.1109/LAWP.2018.2870688
[5] X. Guo, Y. Ding, Y. Duan., X. Ni, Light Sci. Appl., **8**, 123 (2019). DOI: 10.1038/s41377-019-0225-z
[6] M.K.T. Al-Nuaimi, W. Hong, A Mahmoud, in *2017 Sixth Asia-Pacific Conf. on antennas and propagation* (APCAP) (IEEE, 2017), p. 1–3. DOI: 10.1109/APCAP.2017.8420433
[7] B. Lin, B. Wang, W. Meng, X. Da, W. Li, Y. Fang, Z. Zhu, J. Appl. Phys., **119** (18), 183103 (2016). DOI: 10.1063/1.4948957
[8] M.I. Khan, Q. Fraz, F.A. Tahir, J. Appl. Phys., **121** (4), 045103 (2017). DOI: 10.1063/1.4974849
[9] W.M. Boerner, Y. Yamaguchi, IEEE Aerosp. Electron. Syst. Mag., **5** (6), 3 (1990). DOI: 10.1109/62.54634
[10] V.A. Khlusov, Optika atmosfery i okeana, **8** (10), 1441 (1995) (in Russian).
[11] V.A. Khlusov, P.V. Vorob'ov, J. Electromag. Waves Appl., **35** (13), 1687 (2021). DOI: 10.1080/09205071.2021.1892533
[12] S. Taravati, G.V. Eleftheriades, arXiv:2011.08423v1 (31 Oct. 2020). https://arxiv.org/pdf/2011.08423.pdf
[13] A.V. Khristenko, V.A. Khlusov, M.V. Osipov, M.E. Rovkin, in *IEEE 22nd Int. Conf. of young professionals in electron devices and materials (EDM)* (IEEE, 2021), p. 222. DOI: 10.1109/EDM52169.2021.9507601
[14] E.I. Trenkal, V.S. Pozdnyakov, A.G. Loschilov, N.D. Malyutin, in *IEEE 22nd Int. Conf. of young professionals in electron devices and materials* (*EDM*) (IEEE, 2021), p. 23. DOI: 10.1109/EDM52169.2021.9507673
[15] V.I. Gorbunov and V.A. Sutorikhin, Tekhnicheskaya akustika, **10**, 16 (2010). (in Russian) http://www.ejta.org/ru/2010
[16] V. Sutorikhin, Appl. Phys. Res., **4** (4), 8 (2012). DOI: 10.5539/apr.v4n4p8
[17] E.I. Trenkal, V.S. Pozdnyakov, A.G. Loshchilov, N.D. Malyutin, PTE, № 6, 41 (2021). (in Russian) DOI: 10.31857/S0032816221060069