ENERGY TRANSFER BETWEEN LAMB WAVES IN ELECTRICALLY COUPLED LiNbO$_3$ PLATES

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Energy transfer between Lamb waves in a layered piezoelectric structure without acoustic contact, in which separate layers are coupled by means of an electric field, has been studied. An effective energy transfer between direct modes has been found. In addition, a transformation of the direct mode into the backward one was observed at the energy transfer between the plates in the frequency range allowable for backward waves.

Historically, it was volume elastic waves that were first used in acoustoelectronics. With the development of technologies, surface ultrasonic waves found their application as well. Lamb waves are widely used for the non-destructive examination of novel materials with layered structures [1, 2]. However, if the substance layer, in which the Lamb waves propagate, possesses piezoelectric properties, those waves demonstrate some specific features. Recently, the researches on the application of unique properties of waves in plates have been developed. One of the interesting cases is the so-called backward acoustic waves, i.e. the waves with the phase, v_{ph}, and group, v_g, velocities directed oppositely to each other, unlike the case of ordinary direct waves, for which v_{ph} and v_g are directed identically. The existence of backward waves was considered theoretically in detail and proved experimentally in works [3–5].

In this work, an attempt is made to examine the energy transfer in a layered piezoelectric structure without acoustic contact, in which separate layers are coupled by means of an electric field. Namely, we intended to study the features of the energy exchange between direct and backward acoustic Lamb waves. The energy flows for backward transverse normal waves were studied theoretically in work [6], whereas no such researches—neither theoretical nor experimental – were carried out for Lamb waves.

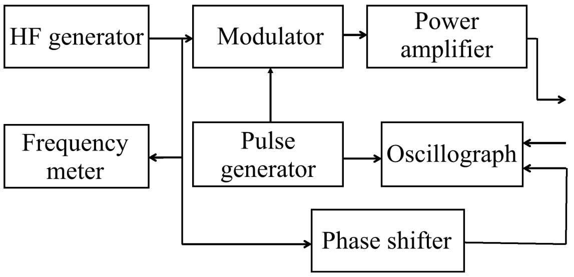

Fig. 1. Block diagram of the experimental setup

A system consisting of two YZ-cut LiNbO$_3$ plates is studied. The plates 4×1 cm^2 in size were cut out from the same crystal. However, they had different thicknesses equal to 640 (plate 1) and 650 μm (plate 2). A small difference in thicknesses is convenient, because, as will be shown further, there may occur a situation where the direct mode is excited in one plate, and the backward one in the other at the same frequency.

The block diagram of the experimental setup is shown in Fig. 1. Making use of a pulse generator and a high-frequency signal generator (HF generator), a radio pulse 2 to 10 μs in duration was formed in the modulator. After amplification, it was applied to an exciting electrode of the studied LiNbO$_3$ plate (the experimental scheme is depicted in Fig. 2). A metal plate 0.5 mm in width was used as an exciting electrode. Owing to the inverse piezoelectric effect, an acoustic wave was excited in the plate. It was registered by the counter electrode which could be shifted along the plate making use of a micrometric screw. The signal on the registering electrode was applied to either of the two-channel oscillograph inputs. The reference signal obtained from an HF-generator and transmitted through a calibrated phase shifter was ap-

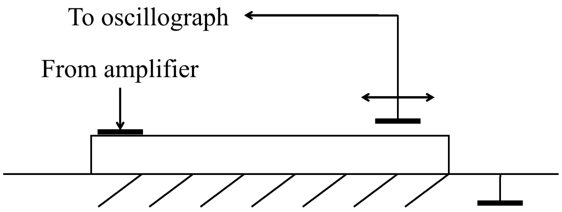

Fig. 2. Experimental scheme for measuring $v_{\mathrm{ph}}(f)$

plied to the other oscillograph input. The sum of both signals was registered by an oscillograph. It allowed a phase shift of the working signal with respect to the reference one to be determined, which made it possible to measure the acoustic wavelength λ (two positions of the registering electrode on the specimen were fixed, for which the working signal had the same phase shift with respect to the reference one). The phase velocity was determined as $v_{\mathrm{ph}} = \lambda f$, where f is the frequency of acoustic waves.

First, we theoretically evaluated the frequencies of Lamb wave generation (the critical frequencies $f_{\mathrm{cr.t.}}$) for individual plates, by analyzing thickness resonances. In those calculations, the propagation velocities for corresponding elastic waves were taken from the reference book [7]. The values of $f_{\mathrm{cr.t.}}$ for the first five modes are quoted in Table 1 (for plate 1) and Table 2 (for plate 2), where the notations QL and QT stand for waves that are generated as quasilongitudinal and quasitransverse, respectively, to the plate thickness.

Using the results of theoretical calculations for critical generation frequencies, experimental researches of excitation of corresponding modes have been carried out. Every mode was excited in a definite narrow range of frequencies close to $f_{\mathrm{cr.t.}}$. In order to associate every mode with theoretical calculations, the experimental value of critical frequency $f_{\mathrm{cr.e.}}$, which was maximally close to the theoretical value $f_{\mathrm{cr.t.}}$ of the corresponding mode, was selected. The experimental values for $f_{\mathrm{cr.e.}}$ are also quoted in Tables 1 and 2.

As is evident from the Tables, two modes, QL_2 and QT_3, are generated in both plates in the vicinity of 10000 kHz. The generation frequencies of those modes, owing to the coincidence of a number of parameters, lie close to each other. As a rule, the mode of the pair, which has a lower generation frequency, can also exist as a backward one [5].

Mode QT_1 was selected for studying the energy exchange between direct modes, whereas modes QL_2 and QT_3 for studying the energy exchange between direct and backward acoustic waves. First of all, the dispersion dependences $v_{\mathrm{ph}}(f)$ for selected modes in each plates were analyzed. The technique used for the determination of the phase velocity was described in work [4]. In addition, a calibrated phase shifter was used in our experimental scheme (see Fig. 1) which allowed not only the magnitude, but also the sign of the phase velocity to be determined. For this purpose, the electrode registering a signal was shifted with respect to the exciting one by a quarter rather than a half wavelength. Depending on whether the phase shift ϕ should be increased or decreased by 90° with the help of a phase shifter (in order to compensate the phase shift of the signal induced by an electrode displacement), the sign of v_{ph} was determined. The two-channel input of an oscillograph gave an opportunity to compare the phases of signals obtained from the specimen and from the phase shifter. The sign of v_{ph} was "+" at $\phi = +90^\circ$ and "−" at $\phi = -90^\circ$. The results of those experiments are presented in Fig. 3.

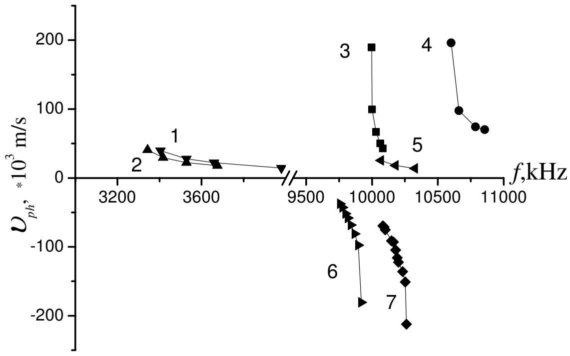

Fig. 3. Dispersion dependences $v_{\mathrm{ph}}(f)$ for Lamb waves in LiNbO$_3$ plates: (*1*) mode QT_1 in plate 1, (*2*) mode QT_1 in plate 2; (*3*) mode QL_2 in plate 2; (*4*) mode QL_2 in plate 1, (*5*) a section of $v_{\mathrm{ph}}(f)$-dependence for mode QT_3 in plate 1 with a direct Lamb wave, (*6*) a section of $v_{\mathrm{ph}}(f)$-dependence for mode QT_3 in plate 2 with a backward Lamb wave, (*7*) a section of the $v_{\mathrm{ph}}(f)$-dependence for mode QT_3 in plate 1 with a backward Lamb wave

The data obtained definitively prove that only the direct waves can expectedly be excited in both plates in the vicinity of 3600 kHz, and both the direct and backward ones in the vicinity of 10000 kHz. Owing to the generation frequency difference between the corresponding modes in both plates in the frequency range 9950 − 10350 kHz, which can be clearly observed by comparing the corresponding plots in Fig. 3, mode QT_3 can propagate in one of the plates. This mode, due to different group velocities, was simultaneously observed as a direct (curve *5*) and a backward one (curve *7*). In the other plate, only the direct QL_2 mode was observed

Table 1. Critical frequencies of Lamb waves in LiNbO$_3$ plate 640 μm in thickness

	QT_1	QL_1	QT_2	QL_2	QT_3
$f_{\mathrm{cr.t.}}$	3508	5375	7016	10750	10524
$f_{\mathrm{cr.e.}}$	3750	5420	7630	10600	10270

Table 2. Critical frequencies of Lamb waves in LiNbO$_3$ plate 650 μm in thickness

	QT_1	QL_1	QT_2	QL_2	QT_3
$f_{\mathrm{cr.t.}}$	3450	5290	6900	10580	10350
$f_{\mathrm{cr.e.}}$	3535	5320	7246	9950	9900

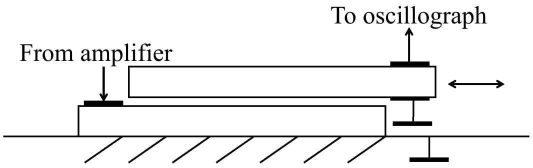

Fig. 4. Scheme of the experiment on the energy transfer between LiNbO$_3$ plates

(curve *3*). All that provides a possibility to study – without extra difficulties – the efficiency of energy transfer between direct and backward waves.

A system of two plates was used for further researches. The waves were excited in plate 1, and the signal was read out from plate 2. The corresponding experimental scheme is exhibited in Fig. 4.

Our researches found the effective energy transfer between direct modes at a frequency of 3650 kHz (the transfer constant $k = A_2/A_1 = 0.65$, where A_1 and A_2 are the amplitudes of the output signal in the cases of one and two plates, respectively). The excitation efficiency for this mode in the system of electrically coupled waveguides is almost the same as that for individual plates.

The energy transfer is no so effective at a frequency of 10230 kHz (the transfer constant $k = 0.05$). Moreover, two separate signals with different time delays were pronouncedly observed at this frequency. They could correspond to a direct wave and a backward one, which are excited simultaneously in plate 1. Since the group and phase velocities for the backward wave are oppositely directed, the signal, which corresponds to the backward wave, should be directed toward the exciting electrode, whereas the signal, which corresponds to the direct wave, should be directed away from it.

To confirm that one of the signals corresponds to the backward wave and the other to the direct one, additional studies of the dependence of the time delay τ of those signals on the distance L between electrodes, which can be varied by shifting one plate with respect to the other, were carried out. The results of those experiments are shown in Fig. 5, where curve 1 corresponds to the backward wave and curve 2 to the direct one. From Fig. 5, one can easily see that the time delay of signal 2 increases, if L grows, which is evident. But the time delay of signal 1 decreases a little at that. Such a delay of signal 1 can be explained by a complicated behavior of this signal in the case where the acoustic wave in plate 1 transforms from a direct wave into a backward one. Then, the time delay in plate 2 will increase, but it will decrease in the system of two plates. It can be explained as follows.

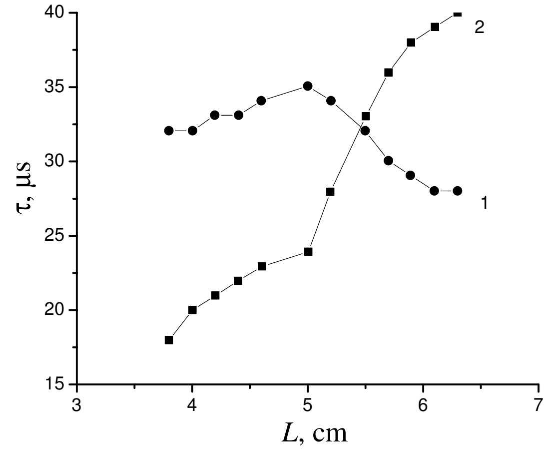

Fig. 5. Dependences of the output signal time delay on the distance between the Lamb-wave exciting and registering electrodes in the system of electrically coupled plates at the energy transfer (*1*) between direct modes and (*2*) between direct and backward modes

Suppose that signal 1 in Fig. 5 corresponds to the backward wave in plate 1. Then, its group velocity is directed oppositely to the phase one. At the same time, if the velocity $v_{\rm ph}$ preserves its direction, when the wave transits from plate 1 into plate 2, the velocity v_g is directed away from the registering electrode. It results in that the backward wave is registered as a mere reflection from the opposite (left) face of the plate. Therefore, the paths for direct and backward waves in the system are different. In the case where the plates have the same length l and they are in either of two extreme positions "one over the other"– 1) the upper plate almost completely covers the lower one ($L \approx l$) and 2) the upper plate is shifted almost to the edge of the lower one ($L \approx 2l$) – we can write down the following expression for the time delays of the backward wave:

$$t_2 = t_1 - \frac{l}{2}\left(\frac{1}{v_{gb}} - \frac{1}{v_{gd}}\right). \tag{1}$$

Here, t_1 and t_2 are the relevant quantities in the first and second cases, respectively; and v_{gb} and v_{gd} are the group velocities of backward and direct waves, respectively. As a rule, $v_{gb} < v_{gd}$ [3], and Eq. (1) testifies that $t_2 < t_1$. This means that if the upper plate is shifted in such a manner that the parameter L increases, the time delay of signal 1 will gradually decrease. That is what was observed in experiment.

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ДОСЛІДЖЕННЯ ПЕРЕДАЧІ ЕНЕРГІЇ ХВИЛЬ ЛЕМБА В ЕЛЕКТРИЧНО ЗВ'ЯЗАНИХ ПЛАСТИНАХ $LiNbO_3$

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Резюме

У роботі досліджено передачу енергії між хвилями Лемба в п'єзоелектричній шаруватій структурі без акустичного контакту, в якій зв'язок між окремими шарами відбувається через електричне поле. Дослідження виявили ефективну передачу енергії між прямими модами. Крім того, в діапазоні частот, де можуть існувати зворотні хвилі при передачі енергії з однієї пластини в іншу спостерігалось перетворення прямої моди у зворотню.