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Relaxation of defect structure in ultrasonic wave field and acoustic emission in LiF single crystals

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Correlation of dependences of acoustic emission parameters and the combination aggregate harmonic amplitude has been studied for two colliding large-amplitude ultrasonic waves in LiF single crystals. This correlation is related to the defect structure relaxation in ultrasonic wave field.

Исследована корреляция зависимостей параметров акустической эмиссии и амплитуды комбинационной суммарной гармоники двух встречных ультразвуковых волн большой амплитуды в монокристаллах LiF. Данная корреляция связывается с релаксацией структуры дефектов в поле ультразвуковой волны.

The structure defects in alkali halide crystals are believed to be rather resistant against influences of elastic fields, induced by ultrasonic waves (USW), that is, the ultrasound is only a factor stimulating the dislocation motion and changes in the metastable structure (local distribution) of the defects as a whole. The dislocation motion is caused by an external loading or the residual elastic stress fields present always in the crystals. The presence of fields different in nature, however, influences both the concentration and state of the structure defects while the defect state changes result in a change of their interaction [1].

The structure reorganization of local domains and defect state changes of crystalline materials may be accompanied by a spontaneous chaotic acoustic emission (AE) of the materials [2–4]. In single crystals under ultrasonic field, this emission is related to simultaneous fixation and breaking-off of dislocation segments on stoppers under translations or vibrations [3, 4], the number of such segments being rather large (up to 10^3 to 10^4 per one AE pulse [2]). The chaotic structure rearrangement in different local domains arising therewith and accompanying the dislocation motion makes it too complicate to consider the wave processes and requires to employ super-intricate nonlinear approximations in wave equations [5].

The nonlinear interaction of large-amplitude USW in crystals accompanied by changes in physical parameters of the solid is also among deviations from linear equations of the crystal state and results in generation of harmonics or onset of combination frequencies [6]. Under certain conditions, both processes, that is, the chaotic structure rearrangement and the nonlinear interaction, may take place simultaneously. The appearance of domains where the structure is changed and the elastic properties are time-dependent must result in a non-monotonous changes (time-dependent "fluctuations") and subsequent relaxation of 3rd order elastic modules, the relative changes its in the latter characterize the efficiency changes of harmonic generation and combination frequencies onset.

In this work, results of first-done simultaneous AE recording and the combination aggregate harmonic (convolution) U_{2f} measurements are presented for two colliding large-amplitude USW in LiF single crystals preliminary treated by high-power ultrasound for long time to provide a non-equilibrium structure defects distribution in the sample.

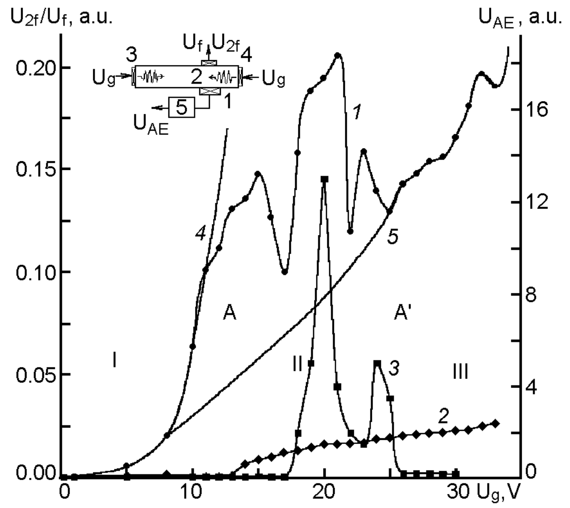

Fig. 1. Dependences of convolution amplitudes and AE on strain generated by a USW of 6.5 MHz frequency. *1*, $U_{2f}/U_f(U_g)$; *2*, $U'_{2f}/U'_f(U_g)$; *3*, $U_{AE}(U_g)$; *4*, approximation of $U_{2f}/U_f(U_g)$ using data of the region I; *5*, approximation of $U_{2f}/U_f(U_g)$ under elimination of the region II data.

To create collinear countercurrent ultrasonic waves of 0.7 to 35.0 MHz range, piezoelectric converters were used (3 and 4, see inset in Fig. 1) where the electric voltage $U_g = 10$ V is in proportion (within linear approximation) to the strain generated thereby $\bar{S} \approx 10^{-4}$ (averaged over the sample length). The AE was recorded in the 20 to 200 kHz range using a piezoelectric transducer (1) and specialized acousto-emission instrument with additional rejecting filter (5) to filter the USW frequencies. A piezoelectric transducer (2) and spectrum analyzer C4-74 were used to measure the main (U_f) and combined (U_{2f}) frequencies of the USW (see Fig. 1). The dependence $U'_{2f}/U'_f(U_g)$ is a the total contribution from nonlinearity of the generator and the transducers (3) and (4). The U_{AE} dependence is the voltage of continuous AE that appeared as groups of noise pulses with subsequent transformation into a pseudo-ordered emission, as in [4].

The line A-A′ in Fig. 1 subdivides the range of strain values generated in the USW field into three regions as well as it confines the region II where fast (up to several times per second) changes (by 20 to 50 %) of U_{2f}/U_f ratio took place in the course of AE. Fig. 1 presents the "final" U_{2f}/U_f values after the AE intensity was decreased significantly or it was over at all. In the I and III regions, the U_{2f}/U_f increases monotonously as the strain rises.

In a medium remaining unchanged as a USW is propagated therein, $T \sim S$ in linear approximation for relatively small strains. The electric voltage amplitude at converters (1), (3), and (4) in no-load operating mode is proportional to the strain, too. Expansion of $T_{ij}(S_{kl})$ function in series shows some deviation from the Hook law even for relatively small strains S_{kl} and S_{rq}:

$$T_{ij} = T_{ij}(0)\Big|_{S_{kl}\to 0} + \frac{\partial T_{ij}}{\partial S_{kl}} \cdot S_{kl}\Big|_{S_{kl}\to 0} + \frac{1}{2}\frac{\partial^2 T_{ij}}{\partial S_{kl}\partial S_{rq}} \cdot S_{kl} \cdot S_{rq}\Big|_{S_{kl}\to 0}^{S_{rq}\to 0} + \ldots \quad (1)$$

Here, the coefficients $\partial T_{ij}/\partial S_{kl}$ and $\partial^2 T_{ij}/\partial S_{kl}\partial S_{rq}$ are the 2nd and 3rd order elasticity modules, respectively, and $T(0)_{ij}$ are residual (elastic and inelastic) mechanical stresses associated with the instantaneous structure of defects, whereas $T(0)_{ij}$ and $\partial^2 T_{ij}/\ \partial S_{kl}\partial S_{rq} \cdot S_{kl} \cdot S_{rq}$ are zero in linear approximation. The changes of $T(0)_{ij}$ and $\partial T_{ij}/\partial S_{kl}$ are taken into account when describing some inelastic effects, such as internal friction, while the change of $T(0)_{ij}$ themselves (changes in local mechanical stresses) manifests itself as the material acoustic emission. The measurement of $\partial^2 T_{ij}/\ \partial S_{kl}\partial S_{rq}$ as a function of $T_{ij}(S_{kl})$ amplitude is rather complicate due to the second item in (1) exceeds the third one considerably. In the same time generation of a strain in the field of two colliding USW makes it possible to evaluate the changes in $\partial^2 T_{ij}/\ \partial S_{kl}\partial S_{rq}$ by measuring directly the relative changes in the interaction (convolution) efficiency.

In the case of $\partial^2 T_{ij}/\ \partial S_{kl}\partial S_{rq} = const$ the dependence $U_{2f}/U_f(\bar{S})$ should be a square-law one, typical of a crystal with unchanging defect structure, that is, $U_{2f} \approx \gamma T_{ij}^2$ or $U_{2f} \approx \delta S_{kl}^2$, where γ and δ are proportionality factors. In Fig. 1 this is valid for the region (I) of relatively small strains (curve 4). In the region II the $U_{2f}/U_f(\bar{S})$ dependence is seen to deviate from the square law. The relaxation of the crystal defect structure due to propagation of colliding USW results in correlation between two types of non-stationary fluctuation processes. The first type ones are those associated with breakdowns of mechanical stresses, that is, time-dependent changes of local $T(0)_{ij}$, first of all, the threshold-type AE appearance. The second type involves fluctuating changes of local 3rd order elastic modules defining the interaction efficiency of colliding USW related to inertia of local rearrangements.

The time-averaged interaction efficiency in the region II lowered as compared to the square-law one is associated with decreasing effective 3rd order modules and evidences the formal linearization of elastic properties at substantially nonequilibrium defect structure state (under fixation and breakdown and motion of dislocations). The threshold AE appearance in the region II and its decrease as the strain rises (USW amplitude grows) may evidence that the strain amplitude $\bar{S}$ exceeds the yield limit $\sigma_{0.2}$ in some local domains. Such a behavior of AE intensity within an interval between the elastic limit σ_E and the yield limit $\sigma_{0.2}$ is well known in the case of static strains [1].

Since the strain changes its sign and value fast enough in our experiments, an "excited" state of the defect structure [4], arises at rather large $\bar{S}$ (the region III). It this case, a fraction of dislocations has no time to be fixed on weak stoppers during the USW half-period and make fast vibrations about the previous equilibrium position due to alternating mechanical strains generated by USW. Since there is no fixation and breakdown at the stopper, there is no AE too. In this case the defect structure changes occur during a time of about one USW period or even less. The traditional quasi-static approximations for 2nd and 3rd order elastic modules seem to become incorrect in consideration of wave processes. At the same time the concept of effective 2nd and 3rd order elastic modules can likely be used; this is evidenced by the square-law character of $U_{2f}/U_f(\bar{S})$ dependence in the region III (Fig. 1, curve 5).

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Релаксація структури дефектів в ультразвуковому полі та акустична емісія у монокристалах LiF

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Досліджено кореляцію залежностей параметрів акустичної емісії та амплітуди комбінаційної сумарної гармоніки двох зустрічних ультразвукових хвиль великої амплітуди у монокристалах LiF. Дана кореляція пов'язується з релаксацією структури дефектів у полі ултразвукової хвилі.