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Light-induced acoustic effect in $LiNbO_3$:Fe:Ce crystals*

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The phenomena of acoustic emission in $LiNbO_3$:Fe:Ce crystals have been observed in the process of light-induced quasi-breakdown. It is found that the ultra-high frequency acoustic signal introduced into the crystal is modulated by the low frequency acoustic waves. Its frequency increases with the increase of the intensity of incident light and its jump period of breakdown is the same as that of the photovoltaic current I_c, the change of light-induced refractive index Δn and the diffracted light intensity L. This phenomenon has been analysed in this paper, which is caused by the inverse piezoelectric strain effect of the jump of space charge field during the quasi-breakdown.

Keywords: photovoltaic current, photo-refractive, space charge field, light induced quasi-breakdown
PACC: 4265, 7820W

1. Introduction

Many investigations on the photo-refractive holographic storage medium in $LiNbO_3$:Fe:Ce crystals have been conducted.[1−5] $LiNbO_3$:Fe:Ce is a typical material for holographic storage, in which a beam of self-enhanced diffracted light will be emitted under the illumination of a coherent visible laser beam. It can be considered as a degenerate four-wave mixing between the incident light and its reflecting light from the back of the crystal and the scattering light due to the defects of the crystal,[6] namely, the self-diffracted light is diffracted from many poly-phase gratings formed by the above-mentioned light beams inside the crystal. Usually, the strength of the light induced space charge field is about 10^5V/cm.[7] Because of this, there exists a process of breakdown,[8,9] i.e., the discharge through the weakly ionized gas passage along the surface of crystal formed under light illumination. We find that some kinds of acoustic effect will occur during the quasi- breakdown in $LiNbO_3$:Fe:Ce crystal under the illumination of coherent visible laser beam. The frequency of acoustic emission increases with increasing incident light intensity and the duration of illuminating time. Its jump period is the same as that of the photovoltaic current I_c, the change of light induced refractive index Δn and the self-diffracted light intensity at a certain position in the space. This acoustic effect can be detected by means of the ultra-high frequency signal induced into the crystal. Through the study of the phenomena, it is thought that this acoustic emission is due to the inverse piezoelectric strain effect of the jump of the space charge field during the light induced quasi-breakdown.

2. Experiments

The samples used here are single-domain $LiNbO_3$:Fe:Ce crystals (0.08mol% Fe, 0.07 mol% Ce). The cross section of the light beam is the X-section. Size of sample 1 and Sample 2 are 10mm × 15mm × 1mm and 15mm× 15mm × 15mm, respectively. The experimental setup is shown in Fig.1. The argon laser has wavelengths λ=488.0nm and 514.5nm.

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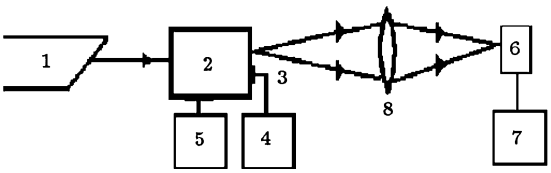


Fig.1. Light induced acoustic effect experimental setup. 1: argon laser; 2: specimen; 3: transducer; 4: transmitter and detector of the ultrasonic signal; 5: electric current detector and amplifier; 6: detector of light intensity; 7: X/Y recorder; 8: lens.

2.1. Relation between the photo-voltaic current and the self-diffracted light intensity of Sample 1

The sample is illuminated by the argon laser beam. Using the photovoltaic current measurement method,[10] the current I_c along the polar axis of Sample 1 is measured. In the meantime, the self-diffracted light intensity at a certain point in space is also measured by means of compensation. The result is shown in Fig.2.

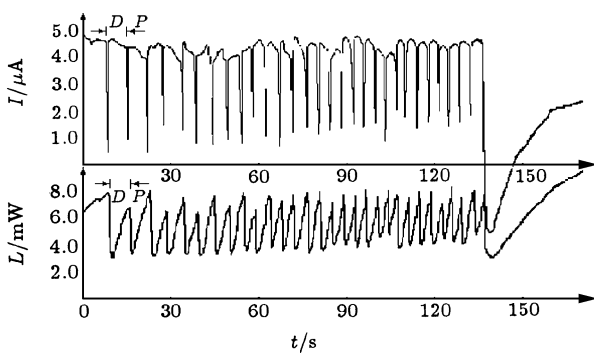


Fig.2. Curves of the photovoltaic current I_c, and the change of diffracted light intensity L. Distance DP denotes the period T. Argon laser λ=488.0nm, laser intensity I=4.96W/cm^2.

As shown in Fig.2, during the light induced quasi-breakdown, the I_c curve jumps down abrupt1y, so will the values of Δn and L simultaneously. And all of these three values have the same jump period. Suppose the time between the jump-down points D and P is one period T. It can be seen from Fig.3 that the jump periods T of the three values are equal to each other and there is a unique process of quasi-breakdown under the illumination of high power light. The frequency of the quasi-breakdown induced by light will increase with the duration of illumination time or increasing of the illumination intensity. Correspondingly, the jump period of the three values will be shortened.

2.2. Relation between the light intensity and the ultrasonic echo with respect to the bulk Sample 2

Using the ultrasonic pulse echo method with the laser beam on Sample 2, we can measure the amplitude of the echoes and display the light induced quasi-breakdown through the change of the self-diffracted light intensity. The result is shown in Fig.3.

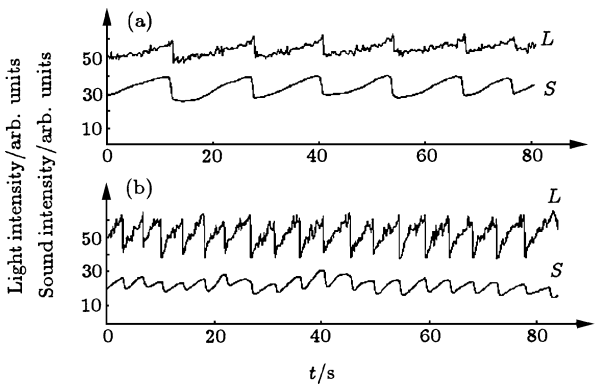


Fig.3. Argon laser λ=488.0nm, (a) I=2.29W/cm^2, (b) I=4.57W/cm^2. L— light signal intensity, S— sound signal intensity.

As shown in Fig.3, the ultrasonic echo is modulated by the low frequency acoustic wave which is induced by the strain in the crystal during the light induced quasi-breakdown. The abrupt jump-down or jump-up of the sound emission occurs at the same time as that of the self-diffraction light intensity. Accordingly, the period T between successive jumps are the same for both signals. When the illumination lasts longer or its intensity increases, the amplitude of both the low frequency acoustic wave S and light intensity L will change correspondingly. Both frequencies are equal as shown in Fig.3(a) and 3(b). It is also found that the wavelength of the argon laser has an influence on the period of both the value L and that of the low frequency acoustic wave S.

3. Discussion of experiment results

3.1. Origin of low frequency acoustic wave

It is considered that the low frequency acoustic wave originates from the inverse piezoelectric strain effect caused by the jumping space charge field when the light induced quasi-breakdown occurs. When a coherent visible laser beam illuminates the crystal, suppose the graph of interference is formed through the interference between the correlative light beams as shown

in Fig.4, in which the light induced space charge intensity is denoted by ρ_{sc}, the change of light induced refractive index by Δn, the space charge field by E_{sc}, the strain by S' which is caused by piezoelectric effect. Corresponding to such a graph as described in Fig.4(b), 4(c) and 4(d).

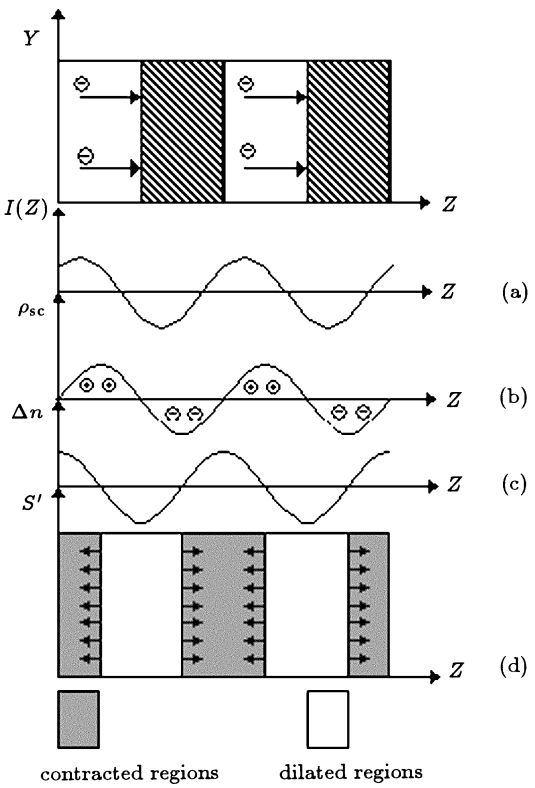


Fig.4. Laser intensity $I(Z)$ 4(a), light induced space charge intensity ρ_{sc} 4(b), space charge field E_{sc} 4(c), piezoelectric induced strain S' 4(d) and the change of light refraction Δn 4(c) along two grating periods. + and − denote the direction of the electric field, where E_{sc} and Δn have the same relation with Z.

The space charge field formed in the $LiNbO_3$:Fe:Ce crystal results from the photovoltaic field and the diffusion charge field.[11] With the increase of the beam radiation time, the space charge field becomes stronger, gradually forming a saturation space charge field. Usually when λ=488nm, I=2.58W/cm^2 (with Sample 1), the obtained stable space charge field intensity can reach 10^5V/cm.[12] Electric field of this magnitude may ionize the air on the surface of the crystal, causing a wide range of charge recombination in the electric field, namely the discharge of the weak ionized gas channel along the surface of the crystal through light, thus leading to the quasi-breakdown of the light reflection crystal.

In the $LiNbO_3$:Fe:Ce crystal, as a result of the crystal inverse piezoelectric strain effect,[13] the piezoelectric strain caused by the space charge field in the crystal brings about the change of the displacement in the crystal. When the quasi-breakdown occurs, the displacement caused by the strain effect in the crystal will change with the space charge field jump, thus resulting in the low frequency acoustic wave. In general, there exists a relaxation time in the process of space charge field growth. Obviously, the piezoelectric strain S' determined by space charge field will change with the space charge field jump and the steady rise, which is the main cause for the occurrence of the low frequency acoustic wave.

Moreover, some thermal effects will occur during the process of gas-discharge. Then this thermal effect will lead to a thermal pulse in the interface of crystal, a part of which can make the temperature of crystal increase and lead to thermal strain and pyro-electric effects.[14] All of these are the basic sources that lead to the creation of the low frequency acoustic wave. But it is the secondary cause under our experimental conditions.

3.2. Change of light scattering intensity and photovoltaic current change curve

When the jump of the light-induced space charge field occurs, because the refractive index is determined by the space charge field[13] ($\Delta n = -\frac{1}{2} n^3 r_{\text{eff}} E_{sc}$, r_{eff} is the effective electro-optic coefficient), the diffraction efficiency of the diffraction grating is changed. The experiment shows that the diffraction intensity has the sudden change in the light scattering intensities curve as shown in Fig.2. At the same time, this kind of gas connects the positive and negative poles of the space charge field in the form of a net and the connection is in parallel with the main loop of the measuring photovoltaic current, therefore its discharge causes a short-circuit. The current of the main loop suddenly drops. When the charge field falls below the discharge threshold, the discharge will stop. At this time, the gas channel is cut off, and the photovoltaic current circulates in the loop. The current curve quickly rises again to the value before quasi-breakdown as shown in Fig.2. This phenomenon indicates that quasi-breakdown is not a bulk effect.[8] But, the light scattering rising curve is different. It is known from Fig.4 that the photorefraction is determined by the space charge field. It will change with the space charge field jump and the steady rise as shown in Fig.2.

3.3. Period of low frequency acoustic wave being the same as that of the jumped Δn, L and I_c

Through analysis of Fig.4 and the above experimental results shown in Fig.2, the photo-refraction and the piezoelectric strain are directly restrained by the space charge field change, therefore the jumping cycle of the space charge field in the crystal determines the change cycles of these parameters, leading to the experimental curve as shown in Fig.3. At the same time, the space charge field changes with the change of the incident light, radiation time, as well as the incident wavelength.[13] Therefore the low frequency acoustic intensity and the scattering light intensity not only has the same change cycle, but also show the change curve with the change of light intensity as shown in Fig.3. In addition, when the quasi-breakdown occurs for laser wavelength λ=488nm measured during the experiment, there exists a threshold of light intensity, i.e. I=0.59W/cm^2, which indicates that the space charge field jump of quasi-breakdown will occur only when this critical incident light intensity is exceeded.

4. Conclusion

The phenomena of acoustic emission in $LiNbO_3$:Fe:Ce crystals have been observed during the process of light induced quasi-breakdown, which are caused by the inverse piezoelectric strain effect in the crystal induced by the jump of space charge field. Through the experimental analysis of light refraction and light diffraction intensity and light induced acoustic intensity, the process and mechanism of light induced quasi-breakdown and acoustic emission are further studied. These results may find applications in new types of all-optical and electro-optical actuators.[15] And this effect has great influence on the field of nonlinear optics, optical wave guide, photo-refraction etc.[1,4,5,8,11,15]

Acknowledgments

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