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Laser-ultrasonic imaging for evaluation of temperature fields in paratellurite optical crystal

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The problem of internal temperature gradients is topical in design of high-performance acousto-optic devices. Current study is focused on the application of laser ultrasound method for evaluation of temperature fields in the paratellurite acousto-optic cell. An automatized laser ultrasonic structuroscope UDL-2M is used to scan the cell surface and to evaluate the temperature distribution from the time-of-flight measurements. The experimental results are presented and precision is discussed. The proposed method has the accuracy of 2−3 degrees Celsius.

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1. INTRODUCTION

Paratellurite (TeO_2) is a common acousto-optic (AO) crystal. Typical configurations of quasicollinear AO devices use a slow shear bulk acoustic wave (BAW) traveling in [110] direction with the interaction length of 40-70 mm along the BAW group velocity direction.[1,2] Attenuation of this wave is of the order of few dB/cm in the frequency range 50-100 MHz. It causes strong and inhomogenious heating of the paratellurite crystal during operation, which leads to the changes of the transmission function. Hence, temperature bias and gradients are important factors in design of high-performance AO devices.[3–7]

Previous studies of the thermal processes in AO cells under typical operation conditions were carried out using finite elements,[3,4] thermal imaging,[5] and optical probing.[6,7] Whilst thermal imaging and optical probing show the general patterns of temperature distribution, they don't image the internal bulk distribution. To this end, ultrasonic thermometry can be used as an extension of previous methods.

2. EXPERIMENTAL TECHNIQUE

An increase of the paratellurite crystal temperature leads to a decrease of the speed of longitudinal BAW, which propagates along the $[1\bar{1}0]$ direction, i.e. orthogonally to the AO diffraction plane. Such dependence is expressed in terms of stiffness coefficients

$$V_L = \sqrt{\frac{c_{11} + c_{12} + 2c_{66}}{2\rho}}, \tag{1}$$

where c_{11}, c_{12}, c_{66} linearly depend on temperature,[6,8] $\rho = 6.0$ g/cm^3 is the crystal density.

The sound speed dependence (1) can be linearly approximated with acceptable accuracy in the temperature range of heating of the AO cell $(20 - 100\,^\circ C)$ by

$$V_L = V_0 + \frac{dV_L}{dT} \cdot (T - T_0), \tag{2}$$

where $\frac{dV_L}{dT} = -0.7\,\mathrm{m/(s \cdot K)}$ and $V_0 = 4468\,\mathrm{m/s}, T_0 = 25\,^\circ C$.

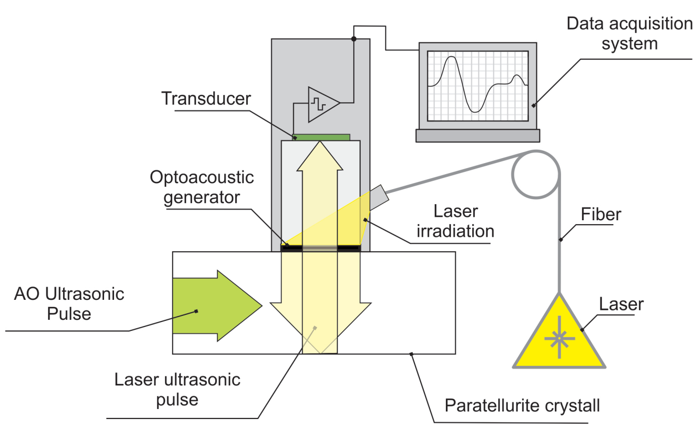


Figure 1: Schematics of the experimental setup for evaluation of temperature fields in the paratellurite acoustooptic cell.

The time of flight of the probing ultrasonic pulse in the medium with inhomogenious temperature distribution can be calculated from path integral

$$t(x, y) = 2N \cdot \int_0^L \frac{dz}{V_L(T(x, y, z))}, \tag{3}$$

where N - number of reflections inside the crystal, L - crystal thickness.

The AO filter design provides only unilateral access for scanning by ultrasonic methods. Thus, with a lack of experimental data, an a priori model of temperature distribution should be used for evaluation of heat parameters. The complexity of the crystal symmetry forces the approximate factorizable by the coordinates models to be used.

In this study, the laser ultrasonic method was used for evaluation of temperature distribution in the AO filter. The excitation of laser ultrasound goes due to the opto-acoustic effect.[9] An absorbtion of short laser pulses in the near-surface layer of a generator material causes a local nonstationary heat and transit expansion of material, which leads to the generation of ultrasonic waves. The advantage of the laser method of ultrasound generation over other methods is the wideband, short acoustic pulses of smooth waveform. This makes laser ultrasound the most precise method for measurements of sound speed.[10]

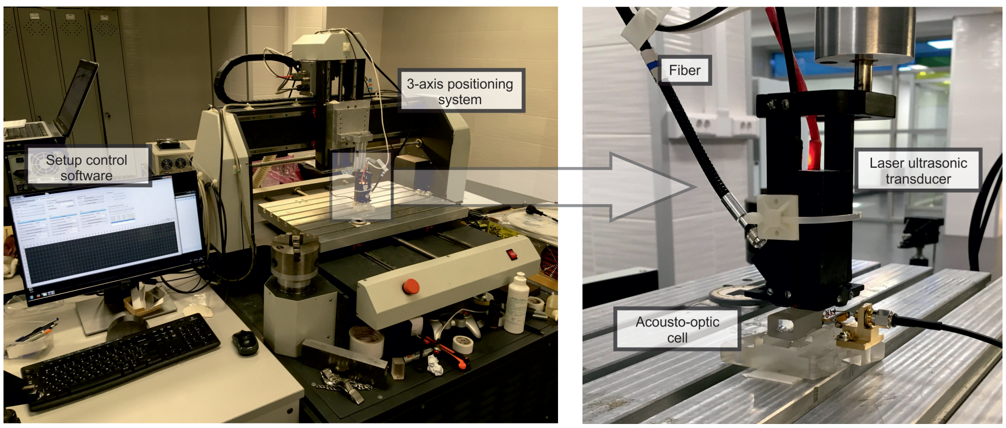


Figure 2: Photographs of the laser ultrasonic structuroscope UDL-2M with the fastened paratellurite AO cell.

The basic scheme of an experimental setup is given in Fig. 1 and its general view is given in Fig. 2. A lithium niobate transducer welded to the AO cell generates the slow shear BAW (frequencies of 115 and 160 MHz are used, power of acoustic radiation is 1.3 W), propagating along the paratellurite crystal and polarized in direction [110]. Absorption of this wave produces temperature gradients in the crystal volume. The AO cell is fastened on the table of the laser ultrasonic structuroscope UDL-2M, which has three translational automatized axes used for scanning.

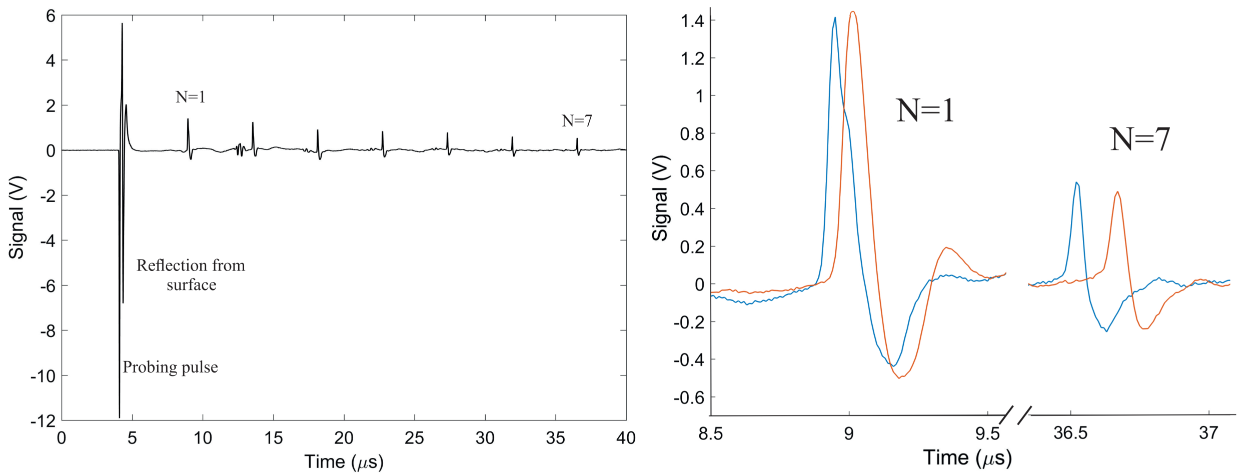
Laser ultrasonic structuroscope UDL-2M is designed as follows. Pulsed radiation of a Nd:YAG laser (pulse duration 10 ns, wavelength 1064 nm, pulse energy 500 μJ, pulse repetition rate 400 Hz) is delivered by a fiber to the absorbing plate (opto-acoustic generator). Generated ultrasonic pulses (longitudinal wave, beam diameter $a \sim 2$ mm, frequency band 0.1-10 MHz) travel in the direction [110] of AO cell perpendicularly to the shear wave and reflect from the back surface of the paratellurite crystal. After that, the pulses are received by a wideband piezoelectric PVDF transducer. Electric signals are amplified, digitized by the ADC (100 MHz, 12 bit), averaged (400 times) and transferred to the PC for further processing. The certified precision of sound speed measurements is 1%, experimetnal precision is 0.1%.[10]

During the pulse propagation laser ultrasonic beam diffracts and its waveform changes to a derivative in time.[9] After that, diffraction negligibly influences the waveform. The diffraction length of the pulse central frequency $f = 5$ MHz in crystal is $L_{diff} = \pi a^2/\lambda \approx 4$ mm. The double flight in the crystal with the thickness of $h = 10$ mm exceeds L_{diff}, therefore the time-of-flight has to be measured between the 1st reflection and the maximally observed 7th reflection (Fig. 3a). Such measurement technique minimizes the influence of diffraction.

The duration of acoustic pulse is 180 ns. Since the sampling frequency is more than twice greater than the signal cut-off frequency, then according to Shannon theorem the signal maximum can be localized using spline more precisely, than sampling time of 10 ns. Taking into account that time is measured between 1st and 7th flights, the experimental accuracy of time measurements is $\Delta t = 0.5$ ns. So, following equation (2) the measurements accuracy of $2 - 3\,°C$ can be achieved.

3. RESULTS

Fig. 3b shows time shift of the signal between the cooled down and stationary (115 MHz) states of the AO filter. Observations show that the shift of the 7th reflection is significant and can be used for evaluation of temperature.



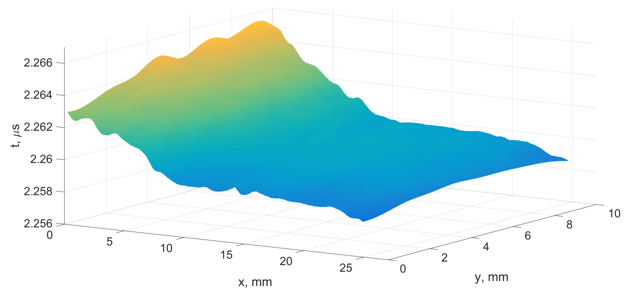
(a) *(b)*

Figure 3: Recorded waveforms. (a) Fully-recorded experimental signal from the cooled down AO cell. (b) 1^{st} ***and*** 7^{th} ***reflections before acoustic pumping of the cell (blue) and after stationary mode is set (red).***

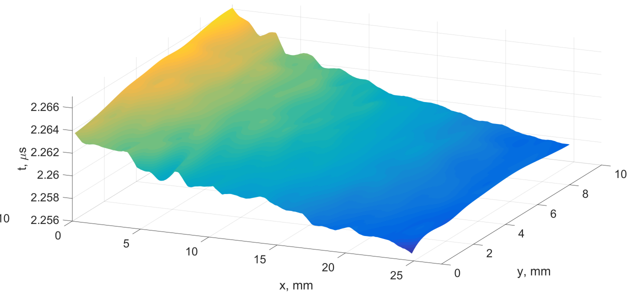
Fig. 4 shows surfaces of the flight times of the laser ultrasonic beam obtained by scanning the paratellurite crystal over the 10×27 mm area with 1 mm step. The longer flight time corresponds to the greater mean temperature in the measurement point. Note that in the stationary regime, the difference between maximum and minimum time of flight is about 10 ns. The highest observed temperature is in the area near the piezoelectric transducer. As it is seen from the surfaces shapes, the laser ultrasonic method allows visualization of temperature gradients in the longitudinal and transversal directions to the shear BAW path. Providing the equal power of acoustic radiation, absorption of the 160 MHz frequency wave is faster than that of 115 MHz. Hence the temperature near the transducer is higher for the case of higher frequency (Fig. 4a), but the surface inclination on the distance from the transducer is more sloping, and temperature is higher for the lower frequency there (Fig. 4b).

4. CONCLUSION

Current paper describes the application of laser ultrasound method based on a priori model for temperature tomography of the paratellurite AO cell. The method is to scan the cell surface using laser ultrasonic structuroscope and to evaluate the 3D temperature distribution from path integrals. The results of experimental measurements are presented and precision is discussed. The proposed method allows evaluation of



(a)



(b)

Figure 4: Surface of the time-of-flight measurements over the scanned by laser ultrasonic structuroscope area. (a) 115 MHz shear BAW pumping. (b) 160 MHz shear BAW pumping.

temperature inside the paratellurite crystal with accuracy of $2-3\,^{\circ}C$ and with spatial resolution of 0.5 mm in XY plane.

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