INTERACTION OF GAUSSIAN LASER BEAM WITH THE ULTRASONIC WAVE OF CYLINDRICAL SYMMETRY

PACS: 43.20.Ks; 43.25.Gf; 43.35.Sx

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ABSTRACT
The theoretical and experimental studies of the interaction between narrow or wide laser beam and standing cylindrical ultrasonic wave were compared. Depending on the ratio of laser beam diameter to the first nodal diameter of cylindrical ultrasound, light refraction or diffraction was observed. Time-average light intensity and modulation of light in the far field of light refraction/diffraction by cylindrical ultrasound were examined. It was revealed that focusing appears if the phase front of the incident light is curved. The focusing efficiency of the considered acousto-optic system depends on the width of the laser beam and curvature of the phase front.

INTRODUCTION
Most of the theoretical and experimental acousto-optic studies were confined to the cases, in which a plane ultrasonic wave or a system of plane acoustic fields (e.g. superposed, adjacent, and spatially separated) was involved. From the practical point of view, considering the interaction of light with ultrasound having cylindrical symmetry seems to be important as the laser output has usually radial symmetry. However, the results given in the reports of Hargrove, Grulkowski and Kwiek [1-3] do not take into consideration the limited radius of curvature of the light beam phase fronts incident on ultrasonic field.

The aim of this paper is to present the results of experimental investigations of light interaction with standing cylindrical ultrasonic wave depending on the width of incident light beam. We show also focusing/defocusing effects when the beam width is comparable to the first nodal diameter of ultrasonic wave and curvature of the light wave front is assumed.

The theories of piezoelectric shell vibrations predict that polarized piezoelectric shell can be a source of various vibration modes. Accordingly, piezoceramic shells have been used in underwater acoustics as the active elements [4]. It has been proven that if the hollow piezoelectric cylinder is coupled to the acoustic medium which the cylinder is filled with, the refractive index distribution of this medium is expressed by the Bessel function of the first kind of zero order \( J_0 \):

\[
n(r, t) = n_0 + n_1 J_0(Kr)\cos(\Omega t),
\]

where: \( n_0 \) is the refractive index of the nondisturbed medium, \( n_1 \) is the amplitude of refractive index variations, \( K \) and \( \Omega \) represent the ultrasonic wave number and circular frequency, respectively [2].

EXPERIMENTAL SET-UP
The designed experimental arrangement is presented in Fig. 1. The ultrasonic field was generated by a radially polarized piezoelectric circular cylindrical shell TR that was closed at both ends by glass windows and filled with water so the ultrasound was mainly generated inwards the acousto-optic cell. The transducer was excited at its fundamental frequency (\( F = \Omega/2\pi = 484 \text{ kHz} \)) of radial vibrations by the signal from a programmable synthesizer/function generator GNR (PM 5193; Philips) amplified by a wideband power amplifier AMP (3100LA, ENI).
The light source used in experiments was a semiconductor laser beam (LDCU 12/6284; Power Technology; \( \lambda = 658 \) nm), whose output beam was expanded by a telescope system EXP. We were able to manipulate the diameter of the beam illuminating the ultrasonic wave by a diaphragm D (Fig. 1a). When we studied interaction of Gaussian laser beam with cylindrical ultrasound, a cw He-Ne laser (HNA-188S; Carl Zeiss Jena; \( \lambda = 632.8 \) nm) was used (Fig. 1b). The photomultiplier PMT with the attached pinhole P (H5783 P, Hamamatsu) acted as a detector. Thus, light intensity could be registered exactly from the centre of the far field pattern. Time-average light intensity was automatically measured by a digital multimeter DMM (PM 2534; Philips), and temporal changes of the intensity of light were determined by means of single photon counting technique using a multichannel scaler/averager MCS (SR 430; Stanford Research Systems; gate width 5 ns).

RESULTS AND DISCUSSION

To make the numerical predictions, we used successive diffraction model in the frame of the formalism of Fourier optics (FO-SDM) [5, 6]. We do not present the details of this method for the sake of brevity.

First of all, we investigated the far field of light diffraction by cylindrical ultrasound. Plane light wave of uniform amplitude distribution across the beam illuminated the cylindrical ultrasonic wave. The results for various beam diameter \( 2R \), presented in Fig. 2, show that the diffraction efficiency of our acousto-optic system increases when the diameter of the beam diminishes.

In the next stage of the studies we measured the light intensity vs. Raman-Nath parameter \( v = kn_1 L \) (\( k = 2\pi/\lambda \); \( \lambda \) - the wave number of the light, \( n_1 \) - the wavelength of light in vacuum, \( L \) – depth of ultrasonic field) when narrow Gaussian laser beam is used. We determined the light beam parameters in the entrance plane of ultrasonic field: the beam width \( w = 1.09 \) mm and the radius of curvature \( \rho = 6.015 \) m. Consequently, we could determine the electric field distribution in the entrance plane of ultrasound:

\[
E(r, z) = \frac{w_0}{w} \exp \left[ -\frac{r^2}{w^2} \right] \exp \left[ -ik \left( z + \frac{r^2}{2\rho} \right) - i\phi \right],
\]

where: \( \phi = \arctan \left( \frac{z}{\pi w_0^2} \right) \), \( w_0 = w(z = 0) \) is the beam waist.

It is important to note here that the laser spot size \( 2w \) was narrower than the first nodal diameter \( d = 2.36 \) mm of ultrasound (\( 2w < d \)).
As indicated in Fig. 3 (a & b), we observed the broadened laser spot rather than separate diffraction orders. Consequently, this phenomenon should be called refraction. Because the Raman-Nath parameter $v$ is proportional to the voltage applied to the transducer, the curve shown in Fig. 3c can be used in calibration purposes.

Fig. 4 presents dependencies of time-average light intensity measured in the centre of refraction/diffraction pattern vs. the Raman-Nath parameter. When wide laser beam interacts with the ultrasound, the light intensity is modulated with the frequency $2\omega$ due to the fact that our acoustic field was actually a standing wave. However, the narrow laser beam is focused since at particular instants normalized light intensity exceeds unity. These focusing/defocusing effects appear due to the fact that light is always bent towards the region of higher refractive index (Fermat's principle).
CONCLUSIONS
We have shown theoretically as well as experimentally that the narrower the laser beam the higher diffraction efficiency of proposed acousto-optic system. A very good agreement of theory and experiment was obtained. Additionally, when the beam width is comparable with the first nodal diameter of ultrasound, such an acoustic field can be regarded as an effective lens. It must be also emphasized that Fourier optical approach to the successive diffraction model (FO-SDM) made it possible to predict all the refraction/diffraction phenomena. The acousto-optic effects presented herein serve as a first step in optimizing the performance of laser light modulators placed either inside or outside the laser resonator.

ACKNOWLEDGEMENTS
This work was supported from the scientific financial resources for 2006-2008 as a research project of the Polish Ministry of Science and Higher Education (# N504 008 31/0453).