

# Acoustooptic Cells with Wedge-Shaped Piezoelectric Transducers Excited at High-Order Harmonics

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**Abstract**—Light diffraction in a nonuniform acoustic field induced by a wedge-shaped piezoelectric transducer is theoretically studied. Electric, acoustic, and acoustooptic characteristics of cells with such transducers are calculated. The emphasis is on the features of cell operation in the case when a piezoelectric plate is excited at the third harmonic. The acoustic field is shown to possess a complex amplitude and phase structure varying with the ultrasound frequency. The efficiency of acoustooptic diffraction depending on the acoustic wave amplitude and phase mismatch is studied. It is established that the efficiency of the Bragg diffraction can approach 100% despite a noticeable phase mismatch. Optimal values for the ultrasound power and angles of light incidence on an acoustooptic cell are found.

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## INTRODUCTION

The problem of excitation of wedge-shaped piezoelectric plates is not new in acoustics [1–4]. The enhanced interest in this problem is caused by two factors. First, it is impossible to fabricate a plate transducer with perfectly parallel faces; therefore, one should know an allowable deviation from parallelism. Second, at a noticeable wedge angle value, the wedge shape of a transducer substantially changes the structure of the acoustic field, which may be useful for the development of various devices.

In the studies mentioned above, wedge-shaped transducers are investigated within the framework of the problem on widening the band of operating frequencies of ultrasound excitation or the creation of an acoustic beam with a scanning pattern. However, the use of such transducers in acoustooptics has certain peculiarities. In order to assess the quality and usefulness of a transducer applied for the solution of acoustooptic (AO) problems, it is insufficient to know integral characteristics of the transducer such as the frequency band and the coefficient of conversion of the electric power into the acoustic power. In addition, one should know the structure of the acoustic field in an AO cell and the variation of this structure with the ultrasound frequency. It was shown in [5–9] that the wedge shape of a piezoelectric plate leads to the amplitude and phase nonuniformity of the acoustic beam excited by the plate. The amplitude nonuniformity only changes the acoustic power value required for obtaining a specified diffraction efficiency.

The phase nonuniformity, which means bending of the beam wave front, is more pronounced. In this case, such an important AO parameter as the Bragg angle loses its sense as it is measured from the acoustic wave front. This means that the condition of phase synchronism cannot be satisfied at any angle of light incidence on an AO cell: there always exists a phase mismatch different at dif-

ferent points of the acoustic field. Therefore, the question on the maximum attainable diffraction efficiency arises. The phase nonuniformity of the acoustic field substantially changes the amplitude, angular, and frequency characteristics of the AO interaction, a circumstance that obviously affects the operation of AO devices. In particular, such an important characteristic as the frequency dependence of the optimal angle of light incidence (i. e., the Bragg angle in a uniform field) is more intricate just in the area of the most effective ultrasound excitation [9, 10].

In this study, the results of calculation of the electric, acoustic, and AO characteristics of cells with wedge-shaped transducers are presented. The emphasis is on the features of the characteristics of such transducers at the third harmonic in comparison with the analogous characteristics for the region of the fundamental excitation frequency.

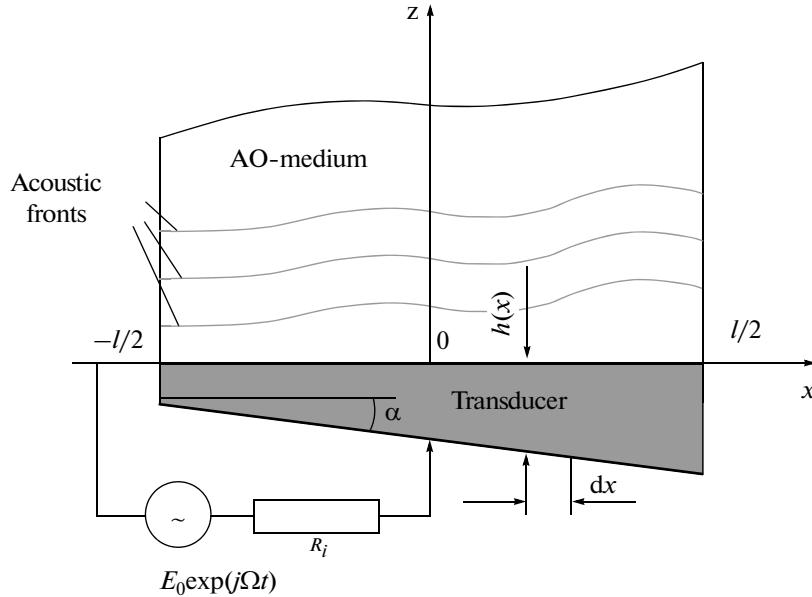
## 1. BASIC RELATIONS

The statement of the problem is illustrated in Fig. 1. A piezoelectric plate with variable thickness  $h(x)$  is fixed on the plane surface of an AO medium. The plate is fed by a sinusoidal voltage with the frequency  $\Omega = 2\pi f$  from a high-frequency (HF) oscillator with emf  $E_0$  and internal resistance  $R_i$ . The dependence of thickness  $h$  of the wedge-shaped transducer on its coordinate  $x$  is

$$h(x) = h_0 + \alpha x, \quad (1)$$

where  $\alpha$  is the wedge angle and  $h_0$  is the plate thickness in the center at  $x = 0$ . The total length of the plate along the  $x$  axis is  $l$ .

We assume that there are no matching elements between the oscillator and the piezoelectric transducer, although, in real devices such elements always exist [11],



**Fig. 1.** Excitation of a wedge-shaped transducer.

[12]. However, wideband matching of complex frequency-dependent impedances is an independent problem well studied in radiophysics [13]. We do not consider this problem, because the aim of our study is to reveal new peculiarities caused by the wedge shape of the transducer.

Assuming angle  $\alpha$  rather small, one can use a known solution to the problem on excitation of a homogeneous piezoelectric plate [14] and write the following expression for the complex admittance of a small section of the plate with dimension  $dx$ :

$$dY = j \frac{\Omega^2 \varepsilon b}{V_0 F(x)} \times \left\{ 1 - \frac{k^2}{F(x)} \frac{Z_a \sin F(x) + 2j[1 - \cos F(x)]}{Z_a \cos F(x) + j \sin F(x)} \right\}^{-1} dx, \quad (2)$$

where  $F(x) = \Omega h(x)/V_0$  is the normalized frequency;  $l \times b$  is the plate dimensions along the  $x$  and  $y$  axes, respectively;  $\varepsilon$  is the permittivity;  $k$  is the piezoelectric coupling coefficient;  $Z_a = \rho_1 V_1 / \rho_0 V_0$  is the relative acoustic impedance;  $V_0$  and  $V_1$  are sound velocities; and  $\rho_0$  and  $\rho_1$  are the densities of the transducer and the AO medium, respectively.

The total admittance of an inhomogeneous transducer is [5, 9]:

$$Y = \int_{-l/2}^{l/2} dY = \frac{1}{R(\Omega)} + j\Omega C(\Omega), \quad (3)$$

where  $R$  and  $C$  are the resistance and capacitance in the parallel equivalent circuit of the transducer.

Radiation resistance  $R$  describes the conversion of the electrical power produced by the HF oscillator into the acoustic power. The ohmic resistance of electrodes and the resistance of dielectric loss of the piezoelectric which cause heating of the transducer are typically low and can be neglected. Equivalent parameters  $R$  and  $C$  intricately depend on acoustic frequency  $\Omega$ .

Relationship (3) allows calculation of the voltage applied to the transducer

$$U = \frac{E_0}{1 + YR_i}, \quad (4)$$

the acoustic power emitted by the transducer to the AO medium

$$P_a = \frac{E_0^2 \operatorname{Re}(Y)}{2|1 + YR_i|^2}, \quad (5)$$

and the coefficient of conversion of the electrical power into the acoustic power (conversion efficiency)

$$\chi = \frac{P_a}{P_{\text{match}}} = \frac{4R_i \operatorname{Re}(Y)}{|1 + YR_i|^2}, \quad (6)$$

where  $P_{\text{match}}$  is the power delivered by the HF oscillator to the matched load  $R = R_i$ . The quantity  $1/\chi$ , measured in decibels is known in acoustics as the conversion loss [15].

To facilitate the numerical calculation, we introduce the following dimensionless parameters:  $A = \alpha l/h_0$ ,

$F_0 = \Omega h_0/V_0$ ,  $X = x/l$ , and  $F(X) = F_0(1 + AX)$ . Then, expression (3) takes the form

$$Y = j\Omega C_0 F_0 \\ \times \int_{-1/2}^{1/2} \left\{ F(X) - k^2 \times \frac{Z_a \sin F(X) + 2j[1 - \cos F(X)]}{Z_a \cos F(X) + j \sin F(X)} \right\}^{-1} dX, \quad (7)$$

where  $C_0 = \epsilon l b / h_0$  is the static capacitance of the piezoelectric plate.

In the case under consideration, the calculation of the characteristics of the AO interaction means solving the problem of light diffraction in a nonuniform acoustic field [16]. The nonuniformity of the field may be caused by poor gluing between the transducer and acoustic line, the diffraction nonuniformity of the field in the near zone, the anisotropy of an acoustic line crystal, etc. But, in any case, such nonuniformity can substantially change the characteristics of AO diffraction. The effect of the near acoustic field nonuni-

formity occurring due to the divergence of an acoustic beam in the presence of strong acoustic anisotropy in a paratellurite crystal near the [110] direction has been analyzed in [17] for the case of an ideally homogeneous piezoelectric transducer. A similar problem has been solved in [18] for a model nonuniformity in the form of a bell-shaped amplitude distribution and a quadratic phase distribution. In this study, according to the problem stated, we consider a realer situation, namely, AO diffraction in an acoustic field with the nonuniformity caused by the wedge shape of the transducer. Following the traditional acoustooptic approach, we assume that a light beam passes through an AO cell near the transducer and that, at the distance equal to the beam width, the structure of the acoustic wave does not change. Under this condition, the deformation amplitude in the acoustic field can be considered as  $z$ -independent and determined in the plane  $z = 0$  as [5 and 9]:

$$a(X) = -j \frac{E_0 e \Omega}{\rho_0 V_0^2 V_1 (1 + Y R_i)} \\ \times \frac{1 - \cos F(X)}{F(X) \sin F(X) - 2k^2 [1 - \cos F(X)] + j Z_a [k^2 \sin F(X) - F(X) \cos F(X)]}, \quad (8)$$

where  $e$  is the piezoelectric constant. Expression (8) is complex: absolute value  $|a(X)|$  describes the distribution of the proper deformation amplitude over the transducer surface, whereas the argument  $\arg(a(X)) \equiv \Phi(X)$  determines the phase distribution. Thus, the transducer with a variable thickness excites an acoustic wave with a complex amplitude and phase structure. Also, it is important to note that this structure strongly depends on ultrasound frequency  $\Omega$ .

The spectrum of AO diffraction is traditionally calculated with the use of coupled wave equations called in acoustooptics the Raman–Nath equations [19, 20]. These equations can be generalized to the case of a non-uniform acoustic field; then, we obtain for the Bragg diffraction [5, 9]

$$\begin{cases} 2 \frac{dC_0}{dX} = q \xi(X) C_1 \exp[j(\eta X - \Phi(X))], \\ 2 \frac{dC_1}{dX} = -q \xi(X) C_0 \exp[-j(\eta X - \Phi(X))], \end{cases} \quad (9)$$

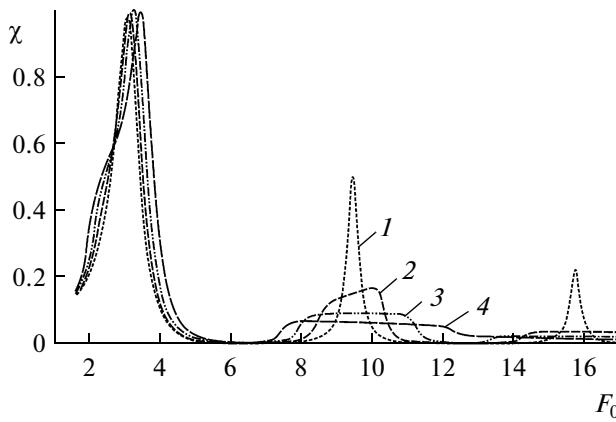
where  $C_0$  and  $C_1$  are the relative amplitudes of the zero- and first-order diffracted waves,  $q$  is the Raman–Nath parameter (AO coupling coefficient) determined at  $A = 0$ ,  $\eta = (\Omega l / V_1)(\theta_0 - \theta_B)$  is the AO phase mismatch,  $\theta_0$  is the angle of light incidence on the AO cell, and  $\theta_B$  is the Bragg angle for a homogeneous acoustic beam. Angles  $\theta_0$  and  $\theta_B$  are measured

from the plane  $z = 0$  of the transducer. Function  $\xi(X)$  proportional to the amplitude  $|a(X)|$  describes the amplitude nonuniformity of the acoustic field and function  $\Phi(X)$  describes the phase nonuniformity. System (9) should be integrated within the range  $-1/2 \leq X \leq 1/2$  with the use of the boundary conditions  $C_0(-1/2) = 1$  and  $C_1(-1/2) = 0$ .

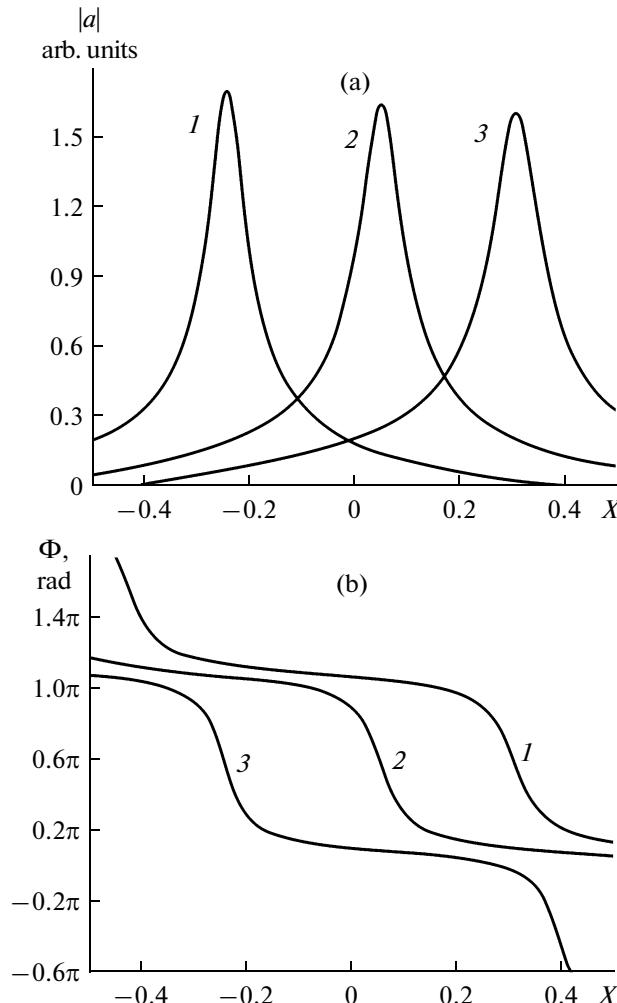
## 2. CALCULATION RESULTS

The numerical calculation based on formulas (4)–(9) is performed for a AO cell made from a zero-degree cut of a paratellurite crystal ( $\text{TeO}_2$ ) with a transducer from  $X$ -cut lithium niobate ( $\text{LiNbO}_3$ ). Such a transducer excites a shear acoustic wave in paratellurite in the [110] direction. In this case, we have  $k = 68\%$  and  $Z_a = 0.166$ . Piezoelectric plate length  $l$  and thickness  $h_0$  are chosen 5.3 mm and 26  $\mu\text{m}$ , respectively. Quantity  $F_0 = \pi$  corresponds to the frequency  $f = 92$  MHz. The calculation is performed for  $R_i = 50$  Ohm.

Piezoelectric transducers normally operate at frequencies near the lowest eigenfrequency. It is known, however, that they can be excited also at odd harmonics [15], but this excitation is rarely used, since, in homogeneous transducers, the generated frequency band narrows and the coefficient of conversion of the electrical power into the acoustic power decreases with an increase in the harmonic number. Our studies have shown that the use



**Fig. 2.** Frequency dependence of the conversion coefficient. Curves 1–4 correspond to  $A = 0, 0.2, 0.35$ , and  $0.5$ , respectively.



**Fig. 3.** (a) Amplitude and (b) phase distributions over the transducer surface at various ultrasound frequencies and  $A = 0.5$ . Curves 1–3 correspond to  $F_0 = 8, 9$ , and  $10.5$ , respectively.

of wedge-shaped transducers can eliminate these negative factors.

Figure 2 depicts the dependence of conversion coefficient  $\chi$  on normalized frequency  $F_0$  for various values of normalized transducer wedge angle  $A$ . Three excitation areas are shown: at the fundamental, third, and fifth harmonics. The case  $A = 0$  corresponds to a homogeneous transducer with thickness  $h_0$ . It is seen that, with an increase in the harmonic number, the conversion coefficient decreases along with effective ultrasound excitation band  $\Delta F$ . In particular, for the third harmonic we have  $\chi^{(3)}/\chi^{(1)} = 0.51$ , and  $\Delta F^{(3)}/\Delta F^{(1)} = 0.44$ . The situation is different for a wedge-shaped transducer: the transducer band broadens. However, this widening is more substantial at the third harmonic than at the fundamental one. For example, for curve 4 ( $\alpha = 0.14^\circ$ ), the band is  $\Delta F^{(1)} = 1.51$  (widening by a factor of 1.76) in the fundamental frequency area, while, in the area of the third harmonic, it is  $\Delta F^{(3)} = 4.97$  (widening by a factor of 13!). Moreover, at the third harmonic, the band turns out to be wider than that for the same wedge angle value at the fundamental frequency by a factor of 3.3 and the frequency characteristic is nearly U-shaped.

The obtained considerable widening of the operating frequency band can be explained by the fact that, in a wedge-shaped transducer, different sections of the plate are effectively excited at different frequencies. It is clearly seen in Fig. 3, which depicts the distribution of acoustic amplitude  $|a(X)|$  and phase  $\Phi(X)$  over the plate surface at different ultrasound frequencies in the third harmonic area for  $A = 0.5$ . The frequency  $F_0 = 9$  is close to the resonance frequency of the central section of the plate. Therefore, the ultrasound excitation is more effective just at the center of the plate (Fig. 3a). With an increase, the excitation maximum shifts to the left, toward the thinner plate end; with a decrease in frequency, the excitation maximum shifts to the right, toward the thicker end.

The phase characteristics (Fig. 3b) actually correspond to the shape of the excited acoustic wave front and indicate that the wave normal direction changes over the transducer surface. For angle  $\gamma$  specifying the wave normal direction, the following relationship is valid:

$$\gamma \approx \frac{V_1 d\Phi}{l\Omega dX} = \frac{V_1 h_0 d\Phi}{V_0 l F_0 dX} = \frac{\varphi_s d\Phi}{2\pi dX}, \quad (10)$$

where  $\varphi_s = V_1/lf$  is the angle of divergence of a homogeneous acoustic beam. The maximum value of the derivative  $|d\Phi/dX|$  in the curves from Fig. 3b is 26.8. Thus, the value of the angle  $\gamma$  variation exceeds  $\varphi_s$  by a factor of 4.3. Comparison with the angle of divergence of an acoustic beam is justified, because all AO devices operate within angle  $\varphi_s$  [19].

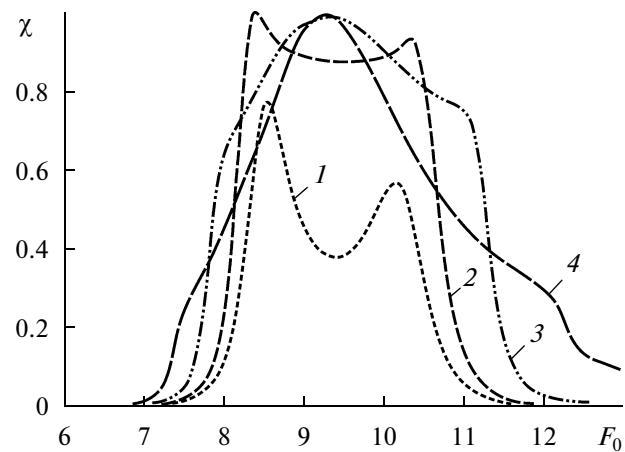
Note that the wave front rotation effect in a wedge-shaped transducer resembles refraction of an acoustic wave propagating through an elastic wedge-shaped plate; however, this effect is actually of another nature. This circumstance is evidenced by the nonlinear character of function  $\Phi(X)$ , its dependence on frequency, and the fact that the maximum rotation of the wave front occurs in the area of the strongest ultrasound excitation. The effect is caused by the phase shift between the voltage across the transducer and the deformation on its surface.

The phase nonuniformity of the acoustic field affects the condition of phase synchronism during the AO interaction. In this case, the common definition of the Bragg angle loses its meaning, as the wave front is curved and the phase mismatch ( $\eta X - \Phi$  in Eqs. (9)) exists at any angle  $\theta_0$  of light incidence. Nevertheless, there is optimal incidence angle  $\theta_{\text{opt}}$  at which the maximum diffraction efficiency is observed.

It follows from Fig. 2 that widening of frequency band  $\Delta F^{(3)}$  with an increase in angle  $\alpha$  is accompanied by the noticeable reduction of conversion coefficient  $\chi$  (by a factor of 7.3 for the case  $A = 0.5$ ). However, as the calculation of the  $C(\Omega)$  has shown, the capacitance variations in the third-harmonic area are much smaller than those in the first-harmonic area. This fact can be used for enhancement of the conversion coefficient by shunting the transducer with the inductance, which, in combination with the capacitance of the piezoelectric plate, would form an oscillatory circuit tuned to the third-harmonic frequency. Thus, the reactivity of the transducer can be appreciably reduced and the most part of the electrical energy can be converted into the acoustic energy.

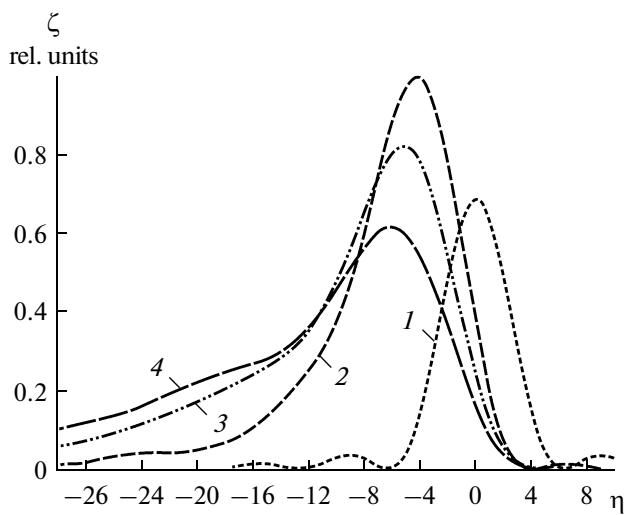
The frequency characteristics of the transducer with the additional inductance chosen so as to correspond to the resonance frequency of the third harmonic  $F_0^{(3)} = 9.46$  are obtained in the third-harmonic area and shown in Fig. 4. One can see the substantial increase of the conversion coefficient for the wedge-shaped transducer with the wide excitation band retained. In particular, for curve 3 ( $A = 0.35$ ) the band is  $\Delta F^{(3)} = 3.39$ , which is wider than the same wedge angle in the first-harmonic area by a factor of 2.8. In this case, the conversion coefficient is nearly 100% and the frequency characteristic is almost U-shaped. It should be emphasized that retaining a wide excitation band is more important than a retaining the high value of the conversion coefficient, which obviously can always be enhanced by adjustment of appropriate matching elements. The wider initial (unmatched) band  $\Delta F$ , the easier providing for wideband ultrasound excitation with the help of a matching circuit.

The amplitude and phase nonuniformity of the acoustic field changes substantially the characteristics of AO diffraction. Angular characteristics in the form

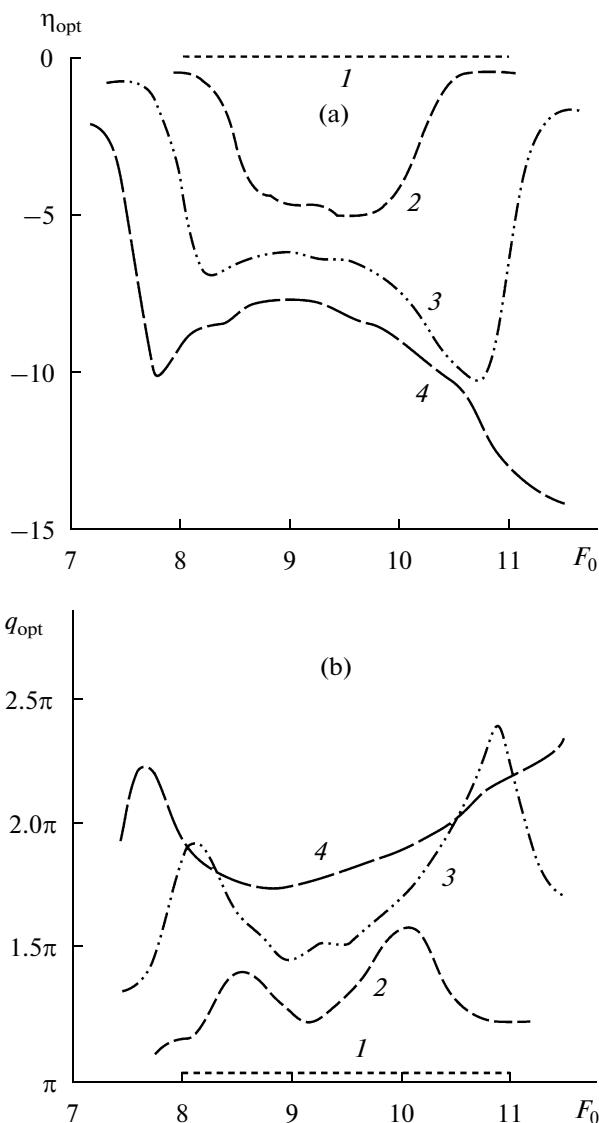


**Fig. 4.** Frequency characteristics of a transducer with an additional inductance. Curves 1–4 correspond to  $A = 0, 0.2, 0.35$ , and  $0.5$ , respectively.

of the dependence of diffraction efficiency  $\zeta = |C_1|^2$  on mismatch  $\eta$  proportional to the deviation of incidence angle  $\theta_0$  from Bragg angle  $\theta_B$  are presented in Fig. 5. The calculation is performed for the frequency  $F_0 = F_0^{(3)} = 9.46$  and the regime of a low diffraction efficiency when the angular dependence of the AO interaction is the Fourier image of the distribution of acoustic amplitude  $a(X)$  [19]. Curve 1 corresponds to the variant of a homogeneous transducer; in this case, dependence  $\zeta(\eta)$  is described by the function  $\text{sinc}^2(\bullet)$ , with the maximum at the phase synchronism point  $\eta = 0$ .



**Fig. 5.** Angular characteristics of an AO cell with a wedge-shaped transducer. Curves 1–4 correspond to  $A = 0, 0.2, 0.35$ , and  $0.5$ , respectively.



**Fig. 6.** Frequency dependences of optimal values (a)  $\eta_{\text{opt}}$  and (b)  $q_{\text{opt}}$ . Curves 1–4 correspond to  $A = 0, 0.2, 0.35$ , and  $0.5$ , respectively.

Note the following features of the angular dependences related to the wedge shape of the transducer. First, optimal angle  $\theta_{\text{opt}}$  of light incidence at which the maximum diffraction efficiency is observed differs from Bragg angle  $\theta_B$ . This fact originates from the rotation of the acoustic beam wave front relative to the transducer plane  $z=0$ . In the case of isotropic diffraction, normalized deviation of angle  $\theta_{\text{opt}}$  from angle  $\theta_B$  is coupled with optimal mismatch  $\eta_{\text{opt}}$  via the formula

$$\delta = \frac{\theta_{\text{opt}} - \theta_B}{\theta_B} = \frac{2}{Q} \eta_{\text{opt}}, \quad (11)$$

where  $Q = 2\pi\lambda/lf^2/n_l V_1^2$  is the Klein–Cook parameter,  $\lambda$  is the light wavelength in vacuum, and  $n_l$  is the refractive index of the AO medium. The optimal angle shift effect is substantial; for example, for curve 4 ( $A = 0.5$ ) we have  $\eta_{\text{opt}} = 6$ . This value should be compared to the condition  $|\eta| \leq 0.89\pi$ , determining the 3-dB AO interaction range [19]. Due to this effect, experimental dependence  $\theta_{\text{opt}}(f)$  noticeably differs from the classical frequency dependence of the Bragg angle [10].

Second, the shape of the angular characteristic changes: it becomes asymmetrical. Third, the characteristic widens (by a factor of 2.2 for curve 4). The last two effects are caused by the fact that the change of the acoustic beam structure is not only the wave front rotation; it is seen from Fig. 3b that, in addition, beam focusing and defocusing are observed on the sections of the quadratic phase variation.

The differences in the maximum values of the diffraction efficiency for different  $A$  are primarily caused by the differences in the conversion coefficients (Fig. 4). In view of this, the question on limiting values of diffraction efficiency  $\zeta_{\text{max}}$  and the corresponding values of the required acoustic power is important.

Figure 6a depicts the dependence of  $\eta_{\text{opt}}$  on acoustic frequency  $F_0$  for various values of wedge angle  $A$ . Horizontal line 1 corresponds to the case of a homogeneous transducer. It is seen that deviation  $\delta$  is large in the area where the transducer operates most effectively. Value  $\delta$  grows with the wedge angle. This result is in good agreement with the experimental data reported in [10].

In the case of the light incidence at the Bragg angle, the diffraction efficiency attains 100% in a uniform acoustic field when the acoustic power provides for the AO coupling coefficient  $q = \pi$  [19, 20]. The phase nonuniformity of the acoustic field does not provide for the phase synchronism condition. Therefore, the question on the maximum attainable diffraction efficiency is of special interest. The detailed calculation has shown that, in the case  $\theta_0 = \theta_{\text{opt}}$ , the diffraction efficiency close to 100% can be reached. An analogous result is reported in [17, 18]. However, this result necessitates an acoustic power higher than that for the case of a uniform acoustic field. Figure 6b illustrates the effect of the nonuniformity of the acoustic field on the diffraction efficiency. Here, frequency dependences  $q_{\text{opt}}(F_0)$  are presented, where  $q_{\text{opt}}$  is the Raman–Nath parameter providing for almost 100% diffraction efficiency at  $\theta_0 = \theta_{\text{opt}}$ . The calculation is performed under the assumption that the acoustic powers in the cases  $A = 0$  and  $A \neq 0$  are the same. This assumption implies that the effect of differences in the transducer impedance is excluded from the calculation. Line 1 corresponds to the homogeneous transducer such that  $q_{\text{opt}} = \pi$  irrespective of frequency. It is seen that the larger the wedge angle, the stronger the

effect of the nonuniformity of the acoustic field; this nonuniformity increases the acoustic power necessary for total pumping of light into the diffraction order.

## CONCLUSIONS

The characteristics of AO cells with wedge-shaped piezoelectric transducers have been studied. It has been shown that such transducers allow substantial widening of the excited frequency band without noticeable reduction of the efficiency of conversion of the electric power into the acoustic one. The excited acoustic beam has a complicated structure characterized by both phase and amplitude nonuniformities. It is important that this structure changes with the ultrasound frequency. Therefore, the characteristics of the AO interaction noticeably differ from the characteristics of AO cells with thickness-uniform transducers. It has been found that the phase nonuniformity affects both the diffraction efficiency and the optimal angle of light incidence on an AO cell. As a consequence, the frequency dependences of the diffraction efficiency and the optimal incidence angle, which play an important role in AO devices, may substantially differ from the corresponding dependences observed in the case of a uniform acoustic field. This result can be used to improve the parameters of such devices.

The advantages of wedge-shaped transducers are more pronounced when such transducers are excited at harmonics, in particular the third harmonic, where the transducer band may widen by a factor of 10. This effect can qualitatively be explained by the fact that the influence of the wedge shape of a piezoelectric plate is determined by the ratio between the plate thickness variation and the ultrasound wavelength. Therefore, the higher the excitation frequency, the stronger the effect of the nonuniformity of the transducer thickness on the frequency characteristic of the device.

## ACKNOWLEDGMENTS

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