A two-frequency mode to control acoustic field distribution inside cylindrical lens

A N Bykhanov

1National Research University Moscow Power Engineering Institute, 14 Krasnokazarmennaya ul., Moscow, 111250, Russian Federation
rubl1009@yandex.ru

Abstract. Acousto-optical (AO) interaction is one of the most effective principles for electronic control of the optical radiation characteristics. Further development of this approach may be related to the use of fluids as a working media. In this paper, it is proposed to optimize spatial distribution of the refractive index in acoustic lens by applying two frequencies simultaneously. The simulation results are given. The optimal frequency combinations in terms of the central lobe intensity are found.

1. Introduction

To solve many problems associated with the use of laser radiation, it is often necessary to control interactively its parameters: intensity, direction, polarization, etc. One of the most effective approaches is AO interaction, i.e. diffraction of light beams on gratings created by ultrasound [1,2]. A sound wave propagates in a transparent medium and creates local sections of mechanical compression and rarefaction of the material in it. The photoelastic effect causes the changes in the dielectric constant and, consequently, in the refractive index. When light passes through such structure, diffraction of light occurs. Thus, the medium in which the ultrasonic wave propagates behaves as a phase lattice.

Further development of AO technologies may be related to the use of liquids as the working medium of AO interaction. This approach allows for the use of complex geometry to obtain acoustic signals of complicated shape. In this paper, we consider a cylindrical AO lens, which allows creating an acoustic field with a Bessel distribution (figure 1). For example, such AO elements are already used for precise focusing of radiation in various areas of modern microscopy [3-6]. In this case, to date, the possibilities of using AO interaction in liquids to control the spectral and amplitude-phase characteristics of optical radiation have not been completely theoretically and experimentally studied.

The diffraction pattern in an acoustic field is determined as the result of multipath interference of coherent diffracted light beams. For this reason, side lobes in the transmission function will appear. This prevents from effective light beams modulation and focusing. The optical radiation should be concentrated at the central lobe. At the same time, due to the small values of acoustic wavelengths, this condition is not always achievable. In this paper, we propose to optimize the spatial distribution of the refractive index in acoustic lens by applying two frequencies simultaneously.
2. Proposed technique.
In the case of a cylinder with radius $R$, the spatio-temporal pressure distribution inside it may be described as [6, 7]:

$$p(r,t) = \Delta p J_0(Kr)\cos(\omega t)$$

where $J_0(Kr)$ is a Bessel function, $K$ and $\omega$ are a wave vector and angular frequency of sound, $\Delta p = \frac{\rho V U_0}{J_1(KR)}$ is a pressure amplitude, $\rho$ is medium density, $V$ is a sound propagation speed in the environment, $U_0$ is a sound wave amplitude.

Modulation of the medium pressure according to (1) leads to the formation of a refractive index distribution in it:

$$n(r,t) = n_0 + \Delta n J_0(Kr)\cos(\omega t)$$

$n_0$ is a refractive index of an undisturbed medium. As shown in [8], when a constant sound frequency $f$ is applied, such acoustic component behaves as a lens with optical power $(K^2\nu/2k)\cos(\omega t)$. $\nu$ is the Raman–Nath parameter.

Concentration of optical radiation in the center of the acoustic distribution is a rather complicated task. Based on this, it follows that it is necessary to minimize the magnitude of the side minima and maxima of the acoustic distribution. Possible solution to this problem is the excitation of two acoustic waves of different frequencies inside an acousto-optical lens.

When applying a two-frequency signal to the piezoelectric transducer, the resulting acoustic field inside the lens will be determined by the principle of superposition.

$$p(r,t, f_1, f_2) = p(r,t, f_1) + p(r,t, f_2)$$

where $f_1$ and $f_2$ are frequencies of electrical signals applied to the piezoelectric transducer.
3. **Modeling**

To find the optimal pair of frequencies, it is necessary to find the sum of two acoustic field distributions of different frequencies, at which the ratio of the central lobe intensity to the total intensity must be maximized. This condition can be expressed as:

\[
\alpha = \frac{\int_0^{r_0} |p(r,t,f_1,f_2)|dr}{\int_0^{\infty} |p(r,t,f_1,f_2)|dr} \cdot 100\% 
\]

where \(r_0\) is the radial coordinate related to the first root of the total distribution. Figure 3 shows the acoustic distributions obtained by applying single-frequency signals to a cylindrical acoustic lens.

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**Figure 2.** Excitation of a two-frequency distribution.

**Figure 3.** The distribution of the acoustic field inside a cylindrical lens in a single-frequency mode with a frequency of 50 kHz (a) and 110 kHz (b).

In case (a), \(\alpha = 44\%\). In case (b), \(\alpha = 30\%\).
As can be seen from figure 3, in a single-frequency mode the intensity of the central maximum does not exceed 50% of the total distribution. By applying a signal with a wavelength comparable with the cylinder diameter, it is possible to achieve high coefficient values, but such frequencies are not suitable for many applications.

Another way to increase the relative intensity of the central lobe is applying two signals of different frequencies simultaneously. Figure 4 shows the examples of acoustic fields obtained in dual-frequency mode using theoretical consideration and modeling in COMSOL.

In cases shown in figure 4, $\alpha$ is 51% (a) and (b), 60% (c), 59% (d). These results suggest that the COMSOL Multiphysics software package suits well for modeling and evaluating multi-frequency acoustic fields.

Using (3), it is possible to determine the optimal pair of frequencies numerically. When sampling frequencies in the interval 10 kHz…300 kHz, the highest value $\alpha = 67\%$ was found by a pair of frequencies: $f_1 = 35$ kHz and $f_2 = 55$ kHz (figure 5). The amplitude difference between the calculated and simulated distributions is caused by the re-reflections of the acoustic wave from the cylinder walls. This effect is taken into account only during modeling in COMSOL.

**Figure 4.** The distribution of the acoustic field inside a cylindrical lens in the dual-frequency mode. Calculation result for the sum of frequencies 40 kHz and 95 kHz (a), simulation result in COMSOL (b), calculation result for the sum of frequencies 40 kHz and 65 kHz (c), simulation result in COMSOL (d).
Figure 5. The dependence of acoustic pressure inside a cylindrical radiating surface while simultaneously exciting two signals with frequencies of 35 kHz and 55 kHz, obtained by calculating (a) and modeling (b).

4. Conclusion
Excitation of an acoustic field inside the AO lens, obtained by supplying two signals with optimal frequencies, can increase the efficiency of light emission control. This conclusion was confirmed by the analytical calculation, which correlates well with the simulation results in the COMSOL Multiphysics software package. The result can be useful for devices such as precision focusers, modulators and spectral filters of Bessel beams, etc. Such devices advantageously distinguish completely electronic control and lower cost compared to existing analogues. They can be widely used in confocal microscopy and optical coherence tomography for manipulating microobjects using optical traps and solving many other problems of modern photonics, where classical crystalline AO elements have long been widely used [9–11].

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