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Decrease in the contrast of the speckle of the optical field using Bragg diffraction of light by sound

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***Abstract*. To decrease the contrast of the speckle of the optical field formed at the output of a multimode optical fibre, it is proposed to use the acoustooptical Bragg diffraction providing a collinear propagation of beams having different polarisation and diffracted to the +1 and −1 orders, and to focus them at the fibre input. This regime provides the 90 % diffraction efficiency. It is shown experimentally that the properties of diffraction in a TeO_2 anisotropic crystal provide an efficient control of the speckle contrast by varying the acoustic frequency, which allows a strong suppression of the speckle.**

Keywords: *speckle, acoustooptical diffraction.*

Due to a rapid development of the means for transmission and processing of optical information, a control of the characteristics of the light field being transmitted and its time and spatial coherence is one of the most important problems [1 – 3]. The propagation of coherent radiation through an extended inhomogeneous medium (air, multimode optical fibre, optical elements with uneven surfaces, etc.) is accompanied by the formation of a field with a small-scale steady-state transverse inhomogeneity called the speckle pattern [2] or the speckle [3], which considerably deteriorates in some cases the characteristics of the information being transmitted. The speckle appears due to interference and hence indicates the spatial coherence of the initial beam. Thus, a direct method for decreasing the speckle of the transmitting optical field involves a destruction of its spatial coherence.

In practice, the methods are often used in which both spatial and temporal coherence of the transmitting optical beam are destroyed. The characteristics of the optical field can be further improved by their time averaging using moving diffuser scatterers [3, 4] and mechanical vibration of the light-guiding medium [5, 6], and also by passing light through liquid crystals in an alternating electric field [7].

Obviously, the characteristic time of variation in the phase of individual rays in the optical beam (and, hence, the destruction time of temporal and spatial coherence) must be much smaller than the time of recording the useful optical signal. In the frequency representation, this means that the frequency of variation in the phase of individual beams in the carrier optical field should be higher than the frequency of the optical signal being transmitted.

In the opinion of a number of researchers [8 – 13], the acoustooptical (AO) interaction is the most promising for solving this problem. This opinion is based on the fact that an acoustic wave is essentially a perturbation of the medium varying in time and space, and can, therefore, be used for the time and spatial modulation of the optical beam. The characteristic frequencies of the AO interaction (5 – 300 MHz) are much higher than the characteristic frequencies of mechanical displacements ($\sim$ 1 kHz [3, 4]) or the frequencies of molecular reorientation (1 – 10 kHz) in liquid crystals [7].

The theoretical and experimental studies of the optical field control using the AO interaction have been performed in many papers; the Raman – Nath [4, 10 – 13] and Bragg [8, 9 14] diffraction regimes have been analysed. However, while the Raman – Nath diffraction regime as applied to the 'mixing' of the light field has been studied extensively both theoretically and experimentally (experiments were carried out at acoustic frequencies up to $\sim$ 10 MHz [4, 8]), the Bragg diffraction regime (at frequencies higher than 20 – 30 MHz) has been investigated only theoretically. It is explained by the fact that it is not easy to attain experimentally a strong distortion of the optical field in the Bragg diffraction regime and thus exert a considerable influence on the parameters of the light field. When conventional acoustooptical Bragg cells are used, the characteristics of the diffracted beam do not differ significantly from those of the incident beam, which makes these cells attractive for the beam control. Significant distortions appear in strongly inhomogeneous acoustic fields [15, 16] or due to repeated overmodulation of the AO interaction [17], which occurs at very high powers of the acoustic wave.

In this work, we propose a method involving the Bragg diffraction without overmodulation, i.e., at a comparatively low acoustic power. The light field in our experiments is formed by two beams corresponding to the +1 and −1 diffraction orders. Because the peculiarities of the AO interaction in an anisotropic medium, the light field of these beams varies differently for the same variation of the acoustic-wave parameters. This makes it possible to enhance the total change in the optical field and to decrease efficiently the speckle contrast (see below).

The method proposed by us employs the polarisation-

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insensitive AO diffraction described in Refs [18, 19]. Fig. 1 shows the optical scheme of the experiment. Radiation from laser (*1*) is incident on AO modulator (*2*) at the Bragg angle to the acoustic wave. The beam diffracted to the +1 order is directed to mirror (*3*) and after reflection crosses the AO cell without repeated diffraction. This beam is focused by lens (*6*) at the input of a multimode optical fibre (*5*). The second part of the laser beam, which did not diffract during its first passage through the cell, is directed to mirror (*4*) and, after reflection, is diffracted to the −1 order from the same acoustic wave. The diffracted beam propagates collinearly with the beam reflected by mirror (*3*) and is also focused at the input of the optical fibre. Note that these beams are shifted in frequency by $2f$, where f is the acoustic wave frequency. The beams are 'mixed' at the end of the fibre. The dependence of the speckle on the parameters of the AO interaction can be observed on screen (*7*).

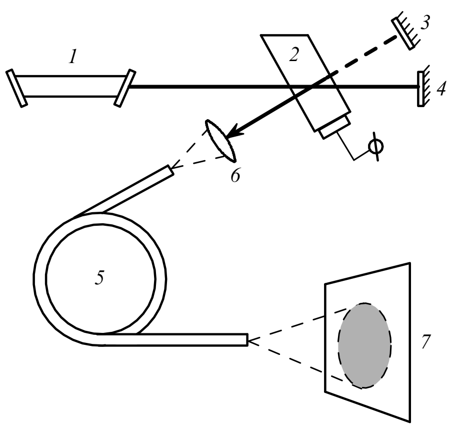

Figure 1. Optical scheme for controlling the speckle pattern: (*1*) laser; (*2*) AO modulator, (*3*, *4*) mirrors, (*5*) fibre, (*6*) lens, (*7*) screen.

We will describe the variation in the diffracted beam profile using the formalism developed in a number of papers, where the AO diffraction was considered from the point of view of plane waves, while the wave profile was taken into account by introducing the instrumental function. In the general case, the amplitude of the plane wave diffracted to the nth order is described in the first approximation by the expression [14, 20–22]

$$\frac{\mathrm{d}E_n}{\mathrm{d}\xi} = -\mathrm{i}\,\frac{\alpha}{2}\exp\left\{-\frac{\mathrm{i}}{2}\,Q\xi\left[\frac{\varphi_{\mathrm{inc}}}{\varphi_{\mathrm{B}}} + (2n-1)\right]\right\}E_{n-1}$$
$$-\mathrm{i}\,\frac{\alpha}{2}\exp\left\{\frac{\mathrm{i}}{2}\,Q\xi\left[\frac{\varphi_{\mathrm{inc}}}{\varphi_{\mathrm{B}}} + (2n+1)\right]\right\}E_{n+1}\,, \qquad (1)$$

where E_n is the complex amplitude of an nth-order plane wave scattered in the direction $\varphi_n = \varphi_{\mathrm{inc}} + 2n\varphi_{\mathrm{B}}$; φ_{inc} is the angle of incidence of light on the acoustic wave front; $\varphi_{\mathrm{B}} = \lambda/2\Lambda$ is the Bragg angle; λ and Λ are the optical and acoustic wavelengths, respectively; $\alpha = CkSL/2$; C is the effective elasto-optical coefficient of the material; k is the propagation constant of light in the medium; S is the amplitude of the acoustic field; L is the length of the AO interaction; $Q = 2\pi L\lambda/\Lambda^2$ is the Klein–Cook parameter; and $\xi = L/z$ is the normalised distance along the AO cell. By choosing the angle of incidence $\varphi_{\mathrm{inc}} = -(1+\delta)\varphi_{\mathrm{B}}$, where δ is the deviation of the angle of incidence relative to the Bragg angle, and considering to the first two diffraction orders (E_0 and E_1), we obtain from (1) the system of equations:

$$\frac{\mathrm{d}E_0}{\mathrm{d}\xi} = -\mathrm{i}\,\frac{\alpha}{2}\exp\left(-\mathrm{i}\,\frac{Q\xi\delta}{2}\right)E_1,$$
$$\frac{\mathrm{d}E_1}{\mathrm{d}\xi} = -\mathrm{i}\,\frac{\alpha}{2}\exp\left(\mathrm{i}\,\frac{Q\xi\delta}{2}\right)E_0, \qquad (2)$$

whose solution for diffraction to the +1 order is

$$E_1(\xi) = -E_{\mathrm{inc}}\exp\left(\mathrm{i}\,\frac{Q\xi\delta}{4}\right)\mathrm{i}\,\frac{\alpha}{2}\left\{\sin\left[\left(\frac{\delta Q}{4}\right)^2\right.\right.$$
$$\left.\left.+\left(\frac{\alpha}{2}\right)^2\right]^{1/2}\xi\left[\left(\frac{\delta Q}{4}\right)^2 + \left(\frac{\alpha}{2}\right)^2\right]^{-1/2}\right\}. \qquad (3)$$

The form of expression (3) makes it possible to introduce the transfer function of a plane wave passing through the Bragg cell. This function is defined as [22]

$$H_1(\delta) = \frac{E_1(\xi = 1)}{E_{\mathrm{inc}}}, \qquad (4)$$

while the distribution of the light field in the +1 order has the form

$$E_1(r) = \int_{-\infty}^{\infty} E_{\mathrm{inc}}(\delta)H_1(\delta)\exp(\mathrm{i}2\pi\zeta r)\mathrm{d}\zeta\,, \qquad (5)$$

where $\zeta \equiv \delta/2\Lambda$. Expression (5) allows us to obtain the profile of the scattered light based on the field distribution of the incident wave.

If the incident beam is Gaussian with the angular distribution [14]

$$E_{\mathrm{inc}}(\delta) = E_{\mathrm{inc}}\exp\left[-\frac{1}{2}\left(\frac{\pi\sigma}{\Lambda}\right)^2\delta^2\right], \qquad (6)$$

where σ is the half-width of the Gaussian beam, the distribution (5) is transformed, taking (3) into account, to

$$E_1(r) = \int_{-\infty}^{\infty} E_{\mathrm{inc}}\exp(-2\pi^2\sigma^2\zeta^2)\left\{\left(-\mathrm{i}\,\frac{\alpha}{2}\right)\exp\left(\mathrm{i}\,\frac{\Lambda\zeta Q}{2}\right)\right.$$
$$\left.\times\mathrm{sinc}\left[\left(\frac{\Lambda\zeta Q}{2}\right)^2 + \left(\frac{\alpha}{2}\right)^2\right]^{1/2}\right\}\exp(\mathrm{i}2\pi\zeta r)\mathrm{d}\zeta\,, \qquad (7)$$

where r and ζ can be treated as variables of the Fourier transform. Numerical calculations of expression (7) show that the profiles of the diffracted beam have a quite complex wavy structure that depends on the parameters of sound (frequency, power) and the incident beam (half-width, the angle of incidence, etc.).

In our experiments, we used the anisotropic diffraction of light by sound, which makes the expression for $E_1(r)$ even more complex. For example, note that the profiles of the beams diffracted to the +1 and −1 orders in an anisotropic medium differ quite significantly: the Gaussian distribution becomes asymmetric and the nature of the field distribution is affected by the 'drift' of optical and acoustic beams [23], etc. For small angular apertures of the optical beams, for example, their ratio is determined [23] by the parameter

$$w = \frac{n_i \cos\beta_d}{n_d \cos\beta_i} \frac{|\boldsymbol{N}_{gr} \times \boldsymbol{q}_{gr}|}{|\boldsymbol{N}_{grd} \times \boldsymbol{q}_{gr}|}, \tag{8}$$

where n_i and n_d are the refractive indices of the incident and diffracted waves, respectively; β_i and β_d are the 'drift' angles of these waves; $\boldsymbol{N}_{gr}$, $\boldsymbol{N}_{grd}$ and $\boldsymbol{q}_{gr}$ are the group normals of the incident, diffracted and acoustic beams, respectively.

It has been shown experimentally that the 'drift' of beams affects considerably the divergence of the diffracted light. Thus, the divergence of beams diffracted to the +1 and −1 orders during the AO interaction in a TeO_2 single crystal may differ by a factor of 2 [23]. In addition, the distributions of the optical fields of the diffracted beams are also different even for the same parameters of the acoustic wave. This factor enhances the efficiency of the method proposed by us for controlling the speckle pattern of the optical field.

The experiments were carried out using the scheme presented in Fig. 1. The light source was an LG-207A single-mode He−Ne laser emitting at 0.633 μm. The AO modulator was made of a TeO_2 single crystal. The face {110} served as the optical face. The diffraction occurred from the transverse acoustic wave propagating in the direction [110] with a shift along the direction [$1\bar{1}0$]. Acoustic vibrations were generated by a $LiNbO_3$ piezoelectric transducer glued to the face {110}, the excitation frequency was $\sim$ 91 MHz (third harmonic of the transducer), the acoustic wave velocity was $v = 6.17 \times 10^4$ cm s^{-1}, and the AO interaction length was $L = 5$ mm.

We used a multimode fibre of length $\sim$ 2 m with a fibre core diameter $\sim$ 50 μm. The focal length of the lens was $\sim$ 25 mm. The AO diffraction was described in detail in papers [18, 19] where the diffraction efficiency of $\sim$ 90 % was observed. It was also shown in these papers that the diffracted beams had different polarisation, namely, the right-hand and the left-hand circular polarisations, caused by the gyrotropy of the TeO_2 single crystal. In other words, the beams incident at the input of the fibre have different frequencies and polarisations, which facilitates the destruction of the speckle of the output optical field.

Fig. 2 shows the photographs of speckle patterns observed on the screen at a distance $\sim$ 10 cm from the output end of the fibre. Fig. 2a corresponds to the case of propagation of a single beam, diffracted to the +1 order [mirror (*6*) in Fig. 1 is covered and only mirror (*3*) is functioning]. Figs 2b−d show the speckles formed by two beams (both the mirrors are uncovered) obtained upon diffraction by an acoustic wave with frequencies 90.8, 91 and 91.1 MHz, respectively. It was shown experimentally that a change in the acoustic power virtually does not affect the contrast of the speckle pattern and only changes its brightness.

A comparison of Fig. 2a with Figs 2b−d shows that the spot size (i.e., the size of the coherence regions [2]) and the contrast of the speckle pattern at the central part of Fig. 2a have much higher values than at the central parts of Figs 2b−d. The weakest contrast of the speckle was obtained in Fig. 2c, when the beams were formed due to the acoustooptical diffraction by sound at a frequency of 91 MHz coinciding with the central frequency of the piezoelectric transducer. In our opinion, two conditions are satisfied quite well in this case: the intensities of both beams are identical, and identical conditions are ensured for the introduction of the beams into the fibre. A variation of the acoustic frequency changes the diffraction angle, which results in the violation of one of the above-mentioned conditions (the contrast of the central part of the speckle in Figs 2b and 2d is manifested more strongly than in Fig. 2c). As for the peripheral regions of the speckle pattern corresponding to the excitation of the higher modes of the fibre, they are virtually repeated in Figs 2a−d.

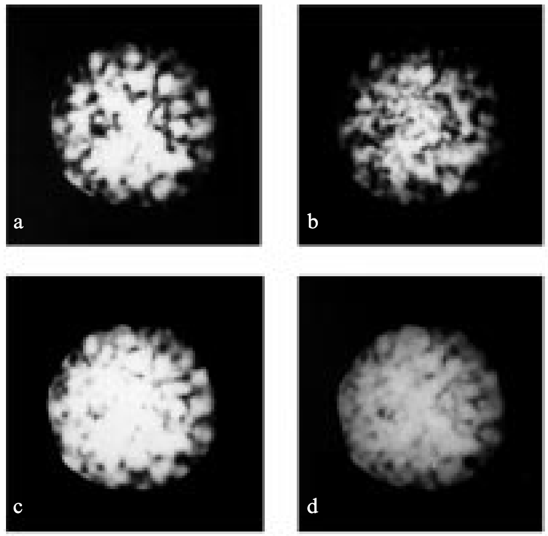

Figure 2. Speckles obtained upon the propagation of one beam (a) and two beams corresponding to acoustic frequencies 90.8 (b), 91 (c) and 91.1 MHz (d).

Further investigations have shown that because of a short length of the fibre ($\sim$ 2 m), the higher modes have time to get excited only by a beam diffracted to the +1 order. If this beam is intercepted and only the beam diffracted to the −1 order is allowed to propagate, the higher modes are virtually not excited. The opposite picture can be obtained by adjusting the input end of fibre: the higher modes are excited only by the beam diffracted to the −1 order, while the beam diffracted to the +1 order does not have time to excite the higher modes. The identical conditions for exciting lower and higher modes of the fibre could not be provided because the beams indeed have different characteristics at the fibre input. The regime shown in Fig. 2d provides the best possible conditions for exciting higher and lower modes by two beams (the speckle has the lowest contrast everywhere). However, this was accompanied by a deterioration of characteristics at the centre of the speckle.

The problem of obtaining the lowest contrast over the entire speckle pattern can be solved by using longer fibres (100−200-m long, according to our estimates). We plan to carry out further investigations of the destruction of the speckle at the output of long fibres.

Thus, the contrast of the speckle of a light beam propagating in a multimode fibre can be reduced by using Bragg diffraction, which provides two collinear radiation beams in two diffraction orders (+1 and −1) with different polarisations. Anisotropic diffraction used in the method proposed here allows the enhancement of the field structure variation and efficiently reduces the speckle contrast. These results can find applications for improving the characteristics of the transmitted optical information.

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