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Effect of optoelectronic feedback on the characteristics of acousto-optical collinear filtering

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Abstract. **The first results of the theoretical and experimental studies of an acousto-optical system with feedback based on a collinear cell made of a calcium molybdate crystal are presented. It is shown that the positive electronic feedback allows essential sharpening of the instrument function of the acousto-optical collinear filter, thus increasing the precision of measuring the optical radiation wavelength.**

Keywords: *acousto-optical interaction, collinear diffraction, light modulation, feedback, acousto-optical filters.*

Acousto-optical (AO) interaction is one of the main effects used to control the parameters of laser light. By now tens of AO devices have been developed, which are widely used in laser physics, optoelectronics and optical processing of information [1]. A number of devices, such as modulators, deflectors and filters are produced serially.

Of particular interest are AO systems with feedback, which, first, allows the improvement of the characteristics of the known devices [2], and, second, allows the development of essentially new ones for laser physics and optical data processing [3 – 8]. In such systems the feedback is hybrid in essence, since optical radiation in the diffraction maximum at the output of the AO cell is converted into an electric signal by means of a photodetector, and this electric signal controls the amplitude [3, 7, 8] or frequency [4, 5] of the acoustic wave excited in the AO cell. The introduction of the feedback essentially complicates and qualitatively changes the behaviour of the AO system [7, 8]. In the present work, the positive optoelectronic feedback in a collinear AO filter is used to narrow the instrument function of the filter and to increase the precision of the optical radiation wavelength measurement.

The schematic of the studied system is presented in Fig. 1. The light from a laser (*1*) passes through a polariser (*2*) and enters a collinear AO cell (*3*) made of a calcium molybdate ($CaMoO_4$) crystal. A longitudinal acoustic wave is excited in the cell by a piezoelectric transducer (*4*) along the crystallographic axis Z and then, after the reflection from the input face of the cell, is transformed into the shear mode, propagating along the X axis collinearly with the incident light beam. An acoustic absorber (*5*) provides the travelling wave regime.

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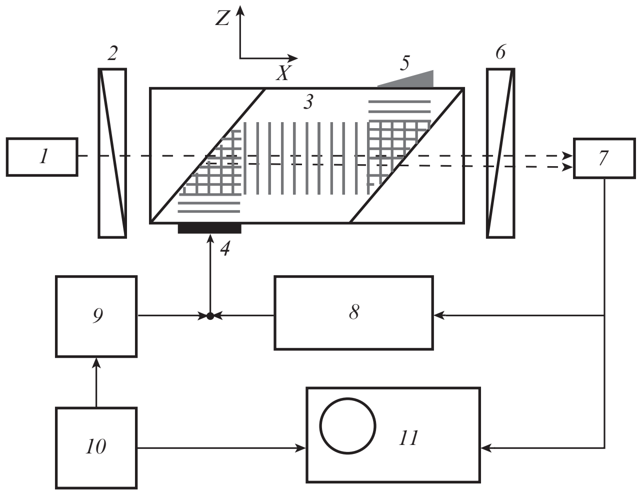

Figure 1. Schematic of the experimental setup:
(*1*) light source; (*2*) polariser; (*3*) AO cell made of the calcium molybdate crystal; (*4*) piezoelectric transducer; (*5*) acoustic absorber; (*6*) analyser; (*7*) photodetector; (*8*) feedback unit; (*9*) HF generator of harmonic oscillations; (*10*) generator of saw-like oscillations; (*11*) oscilloscope.

In the process of light diffraction by the ultrasound, the diffracted wave is generated, propagating in the same direction as the incident one.

In the traditional variant of a collinear AO filter [9, 10] the polarisation of the incident light is set in correspondence with the polarisation of one of the eigenmodes of the crystal (the polarisation angle $\alpha = 0$ or 90°). In the process of AO interaction, the polarisation of light is changed to the orthogonal one (the anisotropic diffraction of light). Due to this fact a cross-analyser (*6*) (with the orientation angle β = 90° or 0) transmits only the diffracted light. The condition of the AO phase matching in the collinear interaction is written as $k_1 = k_0 + K$, where k_1, k_0 and K are the propagation constants for the incident and diffracted light and the ultrasound, respectively [1]. From this relation the unique correspondence follows between the optical wavelength λ_c and the frequency of the ultrasound f_c:

$$\lambda_c = (n_e - n_o)\frac{V}{f_c}. \qquad (1)$$

Here, V is the velocity of sound; n_o and n_e are the crystal refractive indices for the ordinary and extraordinary optical modes. Thus, by varying the frequency of the ultrasound, one can select different spectral components of the optical signal.

The following relation determines the transmission band of the AO filter:

$$\delta\lambda = 0.8\frac{\lambda_c^2}{(n_e - n_o)L}, \qquad (2)$$

where L is the length of the AO interaction (the cell length in the direction of propagation of light and acoustic waves). For example, for $n_e - n_o = 0.0095$, $V = 2.9\times10^5$ cm s^{-1}, and L = 4 cm (the parameters of our filter) at the wavelength λ_c = 632.8 nm we have f_c = 43.6 MHz and $\delta\lambda$ = 0.84 nm.

The intensity of the diffracted radiation I_d can be written in the form:

$$I_d = I_i\frac{\Gamma^2}{4}\mathrm{sinc}^2\left(\frac{\sqrt{\Gamma^2 + R^2}}{2\pi}\right), \qquad (3)$$

where I_i is the incident light intensity; Γ is the Raman–Nath parameter, proportional to the acoustic wave amplitude; and $R = (2\pi L/V)(f - f_c)$ is the AO phase mismatch [1]. Under the phase matching condition (1) the mismatch R = 0 and $I_d = I_i\sin^2(\Gamma/2)$. The diffraction efficiency I_d/I_i amounts to 100% for $\Gamma = \pi$. It is important to note that in the traditional variant of a collinear filter the intensity of the output light remains constant although in the process of diffraction the light frequency ω is shifted by the ultrasound frequency $\Omega = 2\pi f$ due to the Doppler effect.

The situation is quite different when the input polariser is oriented at an angle α = 45°. In this case, the incident light wave in the AO cell divides into two components, the ordinary wave and the extraordinary wave, which diffract simultaneously and with similar efficiency, since the phase matching condition for both of them is valid. As a result, four components appear, two of them having the frequency ω and the other two the frequencies $\omega \pm \Omega$. The beating of these components at the output of the analyser leads to the modulation of the output intensity at the frequency Ω [11, 12]:

$$I_d(t) = I_0 + I_1\cos(\Omega t + \varphi_1). \qquad (4)$$

Here, $I_0 = I_i/2$ is the constant intensity; $\varphi_1(\Gamma, R)$ is the phase shift arising in the process of the AO interaction;

$$I_1 = I_i\frac{\Gamma}{\Gamma^2 + R^2}\sin\left(\frac{\sqrt{\Gamma^2 + R^2}}{2}\right) \times\sqrt{\Gamma^2\cos^2\left(\frac{\sqrt{\Gamma^2 + R^2}}{2}\right) + R^2} \qquad (5)$$

is the amplitude of the first harmonic.

Note that the considered geometry of the filter represents a unique case when the output light appears to be modulated in intensity in the course of diffraction by a travelling monochromatic acoustic wave. This unique feature of the collinear diffraction allows the implementation of the feedback circuit by applying the electric signal from the photodetector to the piezoelectric transducer of the AO cell.

In contrast to the traditional variant of the filter (3), here at R = 0 the amplitude of the first harmonic is $I_1 = (I_i/2)\times\sin\Gamma$. From Eqn (4) it follows that in this case the output light appears to be 100%-modulated when $\Gamma = \pi/2$. Since the parameter Γ is proportional to the square root of the acoustic power, the controlling power is reduced by four times as compared to the traditional variant. It is important to note that in this case the optical losses are completely absent.

Curve (*1*) in Fig. 2 shows the dependence $I_d(R)/I_i$, described by formula (3), calculated for $\Gamma = \pi$. Curve (*2*) presents the dependence $I_1(R)/I_i$ [Eqn (5)] for $\Gamma = \pi/2$. These dependences can be considered as the instrument functions of two variants of AO filters. One can see an essential difference in their shape. Curve (*2*) has a flat top, wider transmission bandwidth and enlarged side lobes. It is worth noting that the side lobes in AO filters create additional parasitic transmission windows that worsen the spectral resolution of the device and reduce the precision of the light wavelength measurements. For such filters, it is possible to introduce the contrast (sharpness) of the spectral characteristic κ as the ratio of the transmission coefficient of the filter in the maximum of the characteristic to that in the first side lobe. Then for curve (*1*) we have κ = 9.1, and for curve (*2*) κ = 3.1. To improve the shape of the transmission function and to increase the spectral contrast it was proposed to use the apodisation of the piezoelectric transducer [13] or to use several cells placed in sequence [14, 15]. In the latter case, it is possible to increase the contrast κ to the value of 65 and to narrow the transmission band by 1.4 times.

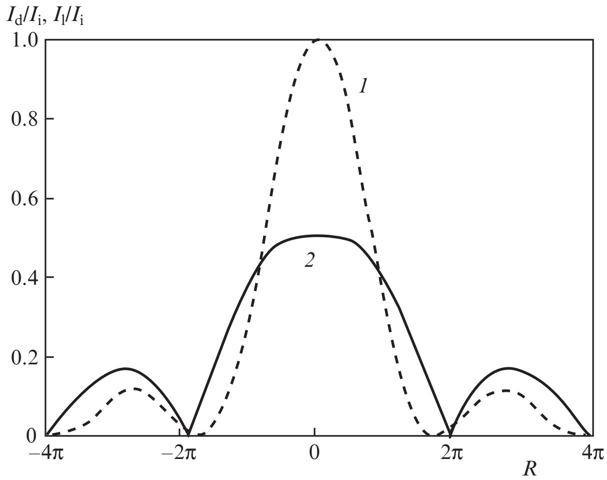

Figure 2. Transmission functions of the AO filter at different mutual orientations of the polariser (α) and analyser (β): $\alpha = 0, \beta = 90°$ (*1*); $\alpha = 45°, \beta = 90°$ (*2*).

In our work to narrow the transmission function, we used the optoelectronic feedback implemented at α = 45°, β = 90°. The diffracted light was recorded by a photodetector (*7*) (Fig. 1), and the detector signal at the ultrasound frequency was applied to a piezoelectric transducer (*4*) via the feedback circuit (*8*) together with the signal of a HF generator (*9*). The feedback circuit incorporated the amplifier with the gain 30 dB and the amplifying phase shifter, providing the optimal phase matching. The frequency of the HF generator was varied by means of a generator of saw-like oscillations (*10*), which allowed the frequency characteristic of the system to be measured. The phase matching was performed manually by changing the value of the capacitor in the phase shifter. In future, we plan to use for this purpose a varicap controlled by the voltage from the generator (*10*). To observe the photodetector signal we used an oscilloscope (*11*) or a radio-frequency spectrum analyser.

In correspondence with the schematic diagram in Fig. 1 the output voltage of the photodetector U_p and the voltage at the piezoelectric transducer U_t are determined by the expressions:

$$U_p = SI_1 \cos(\Omega t + \phi_1),$$
$$U_t = U_g \sin \Omega t + SI_1 K_{am} \cos(\Omega t + \phi_1 + \chi) = \Gamma/\gamma, \quad (6)$$

where S is the voltage sensitivity of the photodetector; K_{am} is the gain of the amplifier; U_g is the amplitude of the voltage from the HF generator; χ is the phase shit introduced by the phase shifter; and γ is the conversion factor of the piezoelectric transducer. The system of equations (4)–(6) allows the calculation of the stationary values of the output voltage U_p. The calculations have shown that the optimal value of the phase shift χ for the phase matching amounts to $-\pi/2$.

The described setup was used to study the effect of the optoelectronic feedback on the characteristics of AO filtering. Figure 3 presents the dependences of the output voltage U_p on the ultrasound frequency (in fact, the instrument functions of the filter) with the feedback circuit switched off. Figure 3a shows the instrument function in the case of the classical orientation of the polarisers, namely, $\alpha = 0, \beta = 90°$. In this case, the photodetector recorded only the diffracted light, and the modulation of the transmitted light intensity was absent. The onset of the oscilloscope sweep occurred synchronously with the variation of the ultrasound frequency. Since in the AO interaction the condition $\lambda f =$ const (1) is valid, the corresponding frequency range can be recalculated into the spectral range $\delta\lambda$:

$$\delta\lambda = -(n_e - n_o) V \frac{\delta f}{f_c^2} = -\lambda_c \frac{\delta f}{f_c}. \quad (7)$$

Experimentally the obtained transmission bandwidth $\delta\lambda$ amounted to 0.9 nm (at the 3-dB level), which is close to the theoretical value of 0.84 nm. Figure 3b illustrates the case $\alpha = 45°$, $\beta = 90°$, when the output signal has a HF carrier at the ultrasound frequency f. In correspondence with the theoretical analysis here the transmission function has a greater width ($\delta\lambda = 1.5$ nm), flattened top and increased side lobes.

The switching on of the feedback in the case $\alpha = 45°$, $\beta = 90°$ essentially changes the shape of the output signal of the system, namely, the amplitude increases, the side lobes vanish, and, what is more important, the transmission band width δf is noticeably reduced (Fig. 4a). The sharpening of the spectral characteristic is caused by the fact that the feedback coefficient is proportional to the photodetector signal amplitude. For the oscillograms presented in the Figure $\delta f = 4.8$ kHz, $\kappa = 60$ and $\delta\lambda = 0.075$ nm. Thus, due to the AO filter-

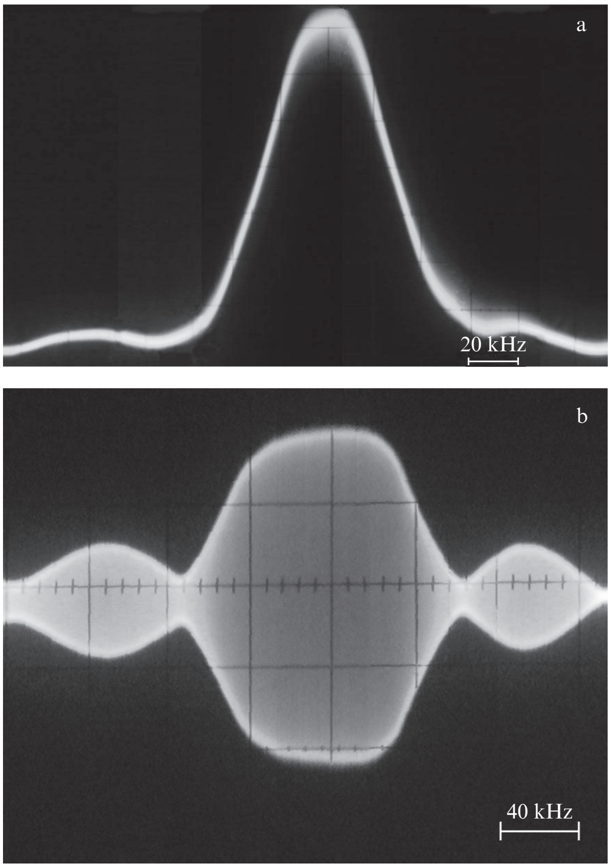

Figure 3. Oscillograms of the photodetector output signal with the feedback circuit switched off in the cases $\alpha = 0, \beta = 90°$ (a) and $\alpha = 45°$, $\beta = 90°$ (b).

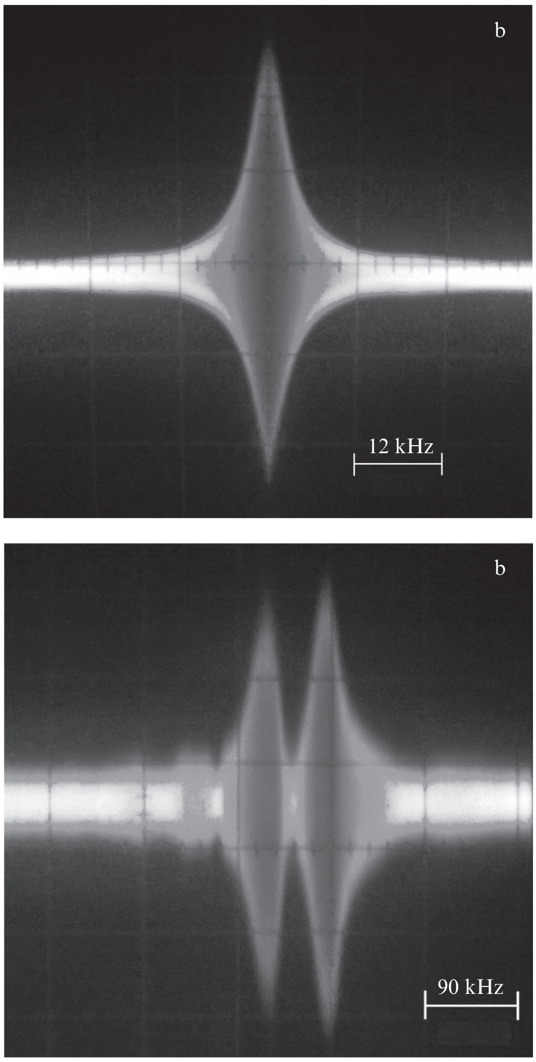

Figure 4. Output signal from the photodetector with the feedback circuit switched on in the cases when the input radiation contains one wavelength (a) and two wavelengths (b).

ing the feedback bandwidth becomes 20 times narrower, which means a similar increase in the light wavelength measurement accuracy. The magnitude of the effect depends on the controlling voltage of the HF generator and the gain of the feedback circuit. The upper limit is determined by the self-excitation of the system. In our experiment, the maximal reduction of the transmission bandwidth δf amounted to 37 times.

Figure 4b shows the shape of the output signal in the case when at the input of the system two laser beams from the injection lasers with the wavelengths 655.2 and 664.7 nm ($\Delta\lambda$ = 9.5 nm) were overlapped. In the classical variant of the filter ($\alpha = 0, \beta = 90°$) the dip in the centre of the transmission function amounted to 15%. The feedback essentially sharpens the spectral characteristic, and we see that the spectral components are completely resolved.

Thus, the performed studies have shown that the use of positive feedback in the collinear AO interaction can significantly narrow the instrument function of the filter, and therefore, increase the accuracy of the wavelength measurement.

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