Acousto-optic Time-Domain Optical Demultiplexer

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Abstract: The design of acousto-optic (AO) time-domain demultiplexer is proposed. The characteristics of such AO device are examined experimentally. This demultiplexer combines the collinear AO tunable filter used for the optical spectrum components selection with the optoelectronic feedback circuit and self-oscillations frequency locking effect. The presented demultiplexer obtain the following characteristics: wavelength spacing between channels may be less than 1 nm, the channel passband width is 0.4 nm, the crosstalk attenuation between adjacent channels exceeds 42dB, the insertion loss is less than 2 dB.

1 INTRODUCTION

Optical demultiplexers are important devices in the fiber-optic communication lines. Many variants of optical demultiplexers have been proposed using various physical effects. Among the variety of such devices were those that applied acousto-optic (AO) effect. In this case, the options for using both surface (Sobrinho, 2004, Ghannam, 2005) and bulk acoustic waves (Kinoshita 1986) were considered. In the case of bulk acoustic waves an AO deflector was used as an element performing spectral selection, either as the main element, or together with the diffraction grating. In this paper, it is proposed for the first time to use a collinear AO filter to create the demultiplexer.

We examine an optoelectronic system that belongs to the class of acousto-optical (AO) devices with feedback (Chrostowski, 1982) in this paper. The signal in the feedback circuit is formed by using a part of the optical radiation intensity from the AO cell optical output that goes to the separate photodetector. The electric signal from this photodetector passes through the feedback circuit connecting its output with the AO cell piezoelectric transducer (Chrostowski, 1982, Balakshy, 2014). It is known that the feedback appearance expand substantially the range of optical information processing problems that can be solved by AO methods (Balakshy, 1996, Chatterjee, 2011).

It was shown earlier (Mantsevich, 2018, Mantsevich, 2018) that several operation modes exist in the system containing the collinear AO filter and optoelectronic feedback circuit. The first one is realized at relatively small values of the feedback gain and is equivalent to the regeneration mode in radio electronics devices. The AO system in this case operates like a tunable AO filter (Harris, 1970, Balakshy, 2007) with one important difference - it is possible to control the bandwidth and spectral contrast by changing the electrical parameters of the feedback circuit (Mantsevich 2018, Mantsevich, 2016, Mantsevich, 2017,).

The second operation mode is the generation mode. It takes place at high feedback gain values (Mantsevich 2018, Balakshy 2004). The amplification factor is so high in this case that it becomes possible to maintain the self-oscillations in the system, so an external RF generator is no longer needed for its operation. The frequency of RF oscillations is being determined by the spectrum of the optical radiation entering the AO filter input and the AO interaction efficiency is controlled by the feedback gain. It was shown earlier (Mantsevich, 2018) that in the generation mode, when connecting the external RF generator, it is possible to observe the AO system self-oscillations frequency locking effect. The locking band width will be determined by feedback gain value and the amplitude of the external RF signal.

In this paper, we examine the possibilities of optical radiation spectral composition controlling that arise when using the frequency locking effect in the examined AO system. The presented investigation shows that this system may be used as

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a time-domain demultiplexer in the optic communication systems.

2 SYSTEM DESCRIPTION

The principal scheme of the examined AO system is shown in Fig. 1. The basic element of the setup is the AO filter with the collinear geometry of acousto-optic diffraction (Harris, 1970). In this geometry, the wave vectors of the incident and diffracted light beams, as well as the wave vector of the acoustic wave excited in the AO cell are collinear.

An optical beam from a light source passes through the polarizer and enters the collinear AO cell. The shear acoustic wave propagating along X crystallographic axis was excited in the AO cell by a piezoelectric transducer. The light beam passes through the cell along the X axis collinear to the acoustic beam. The cell is placed between a polarizer and analyzers that specify the polarization of light at angles α, β and γ with regard to the crystallographic Y-axis. In our experiments, we have used the AO cell fabricated from a calcium molybdate crystal with $l = 4$ cm AO interaction length.

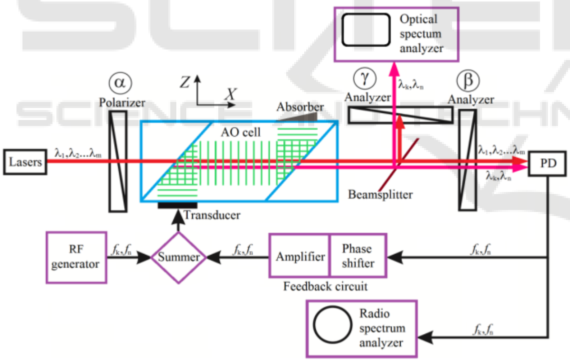


Figure 1: The principal scheme of AO demultiplexer.

A distinctive feature of this AO system from the previously examined (Mantsevich 2017, Balakshy 2016, Mantsevich 2018, Mantsevich 2018) is that the beamsplitter is mounted before of the output polarizers, and the polarization plane of the input polarizer is oriented not at 45 degrees to the Y axis, but is orthogonal to it ($\alpha = 90°$). Such positioning of the beamsplitter allows us to divide the light beam on the AO cell output into two with polarizations controlled independently. One of the light beams passes through the analyzer with the polarization plane orthogonal ($\gamma = 0°$) to the input polarizer polarization plane. This mutual orientation corresponds to the standard application of collinear AO cells when they are placed between crossed polarizers to separate the diffracted light beam from the incident one (Harris, 1970). This optical beam will carry useful information, so let's call it signal. The second beam will pass through the analyzer, with the polarization plane oriented at an angle $\beta = 45°$ to the Y axis. Thus, its intensity will be modulated by amplitude with the ultrasound frequency, excited in the AO cell (Balakshy 2009, Balakshy 2012), which makes it possible to use it for signal generation on the feedback circuit input, so we will call it the feedback beam.

The feedback beam is registered by the photodetector connected to the input of the feedback circuit. The circuit includes phase shifter and amplifier that allow tuning the feedback circuit gain κ over a wide range.

The signal from the feedback output feeds the piezoelectric transducer of the AO cell. Oscilloscope or RF signal spectrum analyzer may be connected to the feedback circuit for the visualization and analysis of the feedback signal characteristics.

The signal beam characteristics were controlled by optical radiation spectrum analyzer with 0.06nm spectral resolution.

Figure 1 presents the schematic diagram of the examined system in the case of its operation in the frequency locking mode. In this variant an external RF generator is used to lock one of the self-oscillation frequencies. The self-oscillation RF frequencies in the feedback circuit are determined by the optical radiation spectrum at the input of the AO cell. If we use the presented system as the demultiplexer only the spectral component with wavelength corresponding to the locked RF frequency will exist in the signal optical beam on the system output.

3 BASIC RELATIONS

The theoretical approach we apply in this paper is based on the model presented in (Balakshy 2016, Mantsevich 2017). First of all it should be mentioned that the phase matching condition for the collinear geometry of AO diffraction is (Harris 1970):

$$f_c = \frac{V}{\lambda}(n_e - n_o) \tag{1}$$

where n_e and n_o are the calcium molybdate refraction indices, V – ultrasound velocity of the slow acoustic mode along the X crystallographic axis that equals 2.91·10^5 cm/s, λ – optical radiation wavelength and f_c is the ultrasound frequency. This equation establishes the correspondence between the incident optical radiation wavelength and the frequency of RF oscillations in the feedback circuit. For the calcium molybdate AO cell used in our experiment the f frequency turned out to be 43.6 MHz for the optical wavelength 632.8nm. The chosen optical wavelength doesn't correspond to the telecommunication wavelengths, but all physical effects that make the examined system operation possible remain fair for longer optical wavelengths. It is also possible to change the calcium molybdate AO cell with lithium niobate cell (Harris 1969) with even higher spectral resolution to shift the optical operation range to near 1.5μm.

It was shown in (Balakshy 2009, Balakshy 2012) that in general case of the polarizers polarization planes orientation the optical beam intensity on the optical output of the system may be described by the following equation:

$$I_d = I_0 + I_1\cos(\Omega t + \phi_1 + \Phi) + I_2\cos(2\Omega t + \phi_2 + 2\Phi) \quad (2)$$

here I_0 is the component that is usually used in collinear AO filters (Harris 1970), it obtains maximal value when polarizer is oriented along or orthogonally to the AO crystal optical axis and analyzer is perpendicular to the polarizer (this is the case of the signal beam in the examined AO system); I_1 component has modulation by intensity with $\Omega = 2\pi f$ frequency that is equal to the ultrasound wave frequency aroused in the AO cell (the feedback beam in the examined system); I_2 is the component that has the amplitude modulation with doubled ultrasound frequency. Variable Φ is the initial acoustic phase at the AO cell input, ϕ_1 and ϕ_2 are the additional phase shifts appearing at collinear AO interaction. In the Eq. (2) all component magnitudes are the functions of polarizer and analyzer polarization planes orientation angles.

It was shown in (Balakshy 2009, Balakshy 2012) that choosing the polarizer and analyzer orientations at angles $\alpha = 90°$ or $0°$ and $\beta = 45°$ or $\alpha = 45°$ and $\beta = 0°$ or $90°$ with regard to the Y crystallographic axis (the second variant was chosen for the feedback beam) we will obtain 100% modulation of diffracted light intensity after the analyzer with ultrasound frequency aroused in the AO cell. In these cases the light intensity of the feedback beam I_{fb} after the analyzer will be described by the following equation:

$$I_{fb}(t) = \frac{I_i}{2}\vartheta + I_i\vartheta\frac{\Gamma}{A^2}\sin\left(\frac{A}{2}\right) \times \sqrt{\Gamma^2\cos^2\left(\frac{A}{2}\right) + R^2\cdot\cos(\Omega t + \phi_1 + \Phi)} \quad (3)$$

where $A = \sqrt{\Gamma^2 + R^2}$, I_i - is the incident light intensity, ϑ is the beamsplitter ratio (50:50 in our case), $\Gamma = (2\pi/\lambda)l\Delta n$ is the Raman–Nath parameter (AO coupling coefficient) proportional to the acoustic wave amplitude aroused in the AO cell, $R = (2\pi l/V)(f - f_c)$ is the dimensionless AO phase mismatch, Δn is the maximal change of the crystal refractive index under the action of the acoustic wave, f - ultrasound frequency, f_c - AO phase matching ultrasound frequency defined by the Eq. (1)

When the AO phase matching condition is fulfilled $R = 0$ and $I_1 = (I_i\vartheta/2)\sin\Gamma$. The amplitude I_1 achieves maximal value $0.5\cdot\vartheta$ at the point $\Gamma = \pi/2$. Thus, at this point, the output intensity changes harmonically in time with the frequency of ultrasound Ω from zero to full intensity of light $I_i\vartheta$. This is the only case in the acousto-optics when AO cell produces amplitude modulation of the optical beam intensity not after the diffraction on the standing but on the travelling acoustic wave.

At the same time the signal beam intensity will be described by the following equation:

$$I_s = I_i(1-\vartheta)\frac{\Gamma^2}{4}\cdot sinc^2\left(\frac{\sqrt{\Gamma^2 + R^2}}{2\pi}\right) \quad (4)$$

The additional phase shift ϕ_1 appearing at collinear AO interaction is defined by the equation:

$$\tan\phi_1 = \frac{\sqrt{\Gamma^2 + R^2}}{R}\cot\left(\frac{\sqrt{\Gamma^2 + R^2}}{2}\right) \quad (5)$$

So we need to include the phase shifter in the feedback circuit to fulfill the phase balance condition defined by Eq.(5). It is easy to see that if the phase matching condition is fulfilled and R=0 the $\phi_1 = \pi/2$

The detector signal that is also the signal on the feedback circuit input equals $U_{fb}(t) = \sigma\, I_{fb}(t)$ where σ is the sensitivity of the photodetector (V/W). We have chosen $\sigma = 0.7$ for the calculations. After passing the feedback circuit $U_{fb}(t)$ feeds the AO cell piezoelectric transducer. Thus the RF signal on the transducer may be described by the following equation:

$$U(t) = \sigma\kappa\vartheta I_i \frac{\Gamma}{A^2} \sin\left(\frac{A}{2}\right) \cdot \sqrt{\Gamma^2 \cos^2\left(\frac{A}{2}\right) + R^2} \cdot \cos(\Omega t + \phi_1 + \Phi + \chi) \quad (6)$$

here, κ is the amplifier gain factor, and χ is the phase shift produced by the phase shifter. The Eq.(6) value will be maximal if:

$$\chi = -\phi_1 = -\frac{\pi}{2} \quad (7)$$

This equation indicates that the phase shifter has to compensate the AO phase shift ϕ_1. And then it is possible to rewrite Eq. (6) as:

$$U(t) = U_0 \cos(\Omega t + \Phi) \quad (8)$$

$$U_0 = \sigma\kappa\vartheta I_i \frac{\Gamma}{A^2} \sin\left(\frac{A}{2}\right) \cdot \sqrt{\Gamma^2 \cos^2\left(\frac{A}{2}\right) + R^2} \quad (9)$$

The Raman–Nath parameter Γ is proportional to the acoustic wave amplitude and, consequently, to the electrical voltage amplitude U_0 applied to the transducer:

$$\Gamma = \mu U_0 \quad (10)$$

where μ is transformation the coefficient determined by characteristics of the transducer and the AO cell. Measuring the characteristics of the collinear AO filter used in experimental setup we have defined that $\mu = 0.9$.

Finally it is possible to write the relation that describes the behavior of the examined AO system:

$$\Gamma = \mathrm{K} \frac{\Gamma}{A^2} \sin\left(\frac{A}{2}\right) \cdot \sqrt{\Gamma^2 \cos^2\left(\frac{A}{2}\right) + R^2} \quad (11)$$

here $\mathrm{K} = \sigma\kappa\,\mu\vartheta I_i$ is the generalized feedback coefficient. Eqs. (5) and (11) form the phase and magnitude balance conditions for the examined system.

The examined system operates above the excitation threshold and it is possible to treat it as the AO generator (Balakshy 1996, Balakshy 2004).The feedback gain is high enough to maintain the constant magnitude of the self-oscillations in the feedback circuit without the signal from RF generator. Considering the phase and amplitude balance conditions it is possible to rewrite the Eq. (11) and Eq. (5) to define the system self excitation border:

$$\frac{\mathrm{K}}{\Gamma_g^2 + R_g^2} \sin\left(\frac{\sqrt{\Gamma_g^2 + R_g^2}}{2}\right) \cdot \sqrt{\Gamma_g^2 \cos^2\left(\frac{\sqrt{\Gamma_g^2 + R_g^2}}{2}\right) + R_g^2} = 1 \quad (12)$$

$$\tan \Phi_g = \tan\left(\Phi_g + \phi_g + \chi_g\right) - R_g \quad (13)$$

The missmatch $R_g \to 0$ in the generation mode. It is possible to obtain the gain values corresponding to the system excitation threshold from Eq. (12). We should consider the missmatch $R_g = 0$ to define the excitation threshold. Then threshold feedback coefficient values will be described by equation:

$$\kappa = \frac{2\Gamma_g}{\sigma\mu\vartheta I_i \sin \Gamma_g} \quad (14)$$

Considering Eq.(13) and (14) it s possible to notice that there is no dependence on optical radiation wavelength, only intensity is involved. So if optical radiation on the optical input of the system contains several spectral components with intensities higher than those required by Eq. (14), then the frequencies corresponding to them in accordance with Eq. (1) will be excited in the feedback circuit and in the AO cell. Thus all these wavelengths will exist at the optical output of the AO system.

The Eq. (13) also indicates that the system passband will tend to zero in the generation mode.

If we assume that the AO cell and detector are ideal and that the incident optical radiation intensity is $I_i = 1$ the threshold value of the gain κ corresponding to the transition from the regeneration mode to the generation mode will be equal to $2/\vartheta$ where ϑ is the beamsplitter ratio. We use 50:50 beamsplitter since in this case it is convenient to examine both output and feedback signals. So the theoretical κ threshold value in ideal case equals 4. In our system $\mu = 0.9$ and $\sigma = 0.7$ so theoretical threshold gain value is $\kappa = 6.35$. At the same time we obtain experimental threshold amplification factor values higher than 100. This discrepancy is caused by the fact that in the experiment the light beam has a certain intensity that is not equal to a unit as it is assumed in theoretical calculations.

4 SYSTEM OPTICAL CHARACTERISTICS EXAMINATION

The most interesting question related to the optical characteristics of the presented AO system is the examination of its real passband. The measurement was fulfilled in the following way. The ThorLabs CPS635R laser module was used in the experiment. This module has many optical radiation modes in comparatively broad waveband. The optical radiation spectrum of this module was measured by optical spectrum analyzer with 0.06nm spectral resolution. The results of this measurement are illustrated by curve *1* in Fig.2.

The spectrum of the signal optical beam was measured for two cases. In the first case the AO system was operating without feedback like the conventional collinear AO filter (curve *2*) and in the second case it was operating in the generation mode (curve *3*). It is known that the half-width of the AO filter used in experiment without feedback is 0.9nm. So we may notice the influence of the filter transmission on the laser modes between 636 and 636.3 nm.

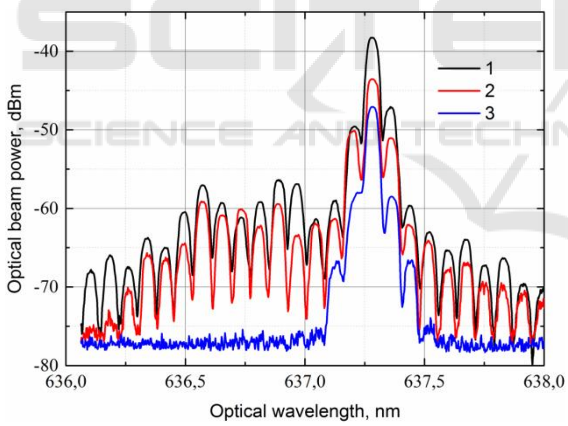


Figure 2: The measured optical radiation spectra. 1 - ThorLabs CPS635R laser module spectrum; 2 – AO system without feedback; 3 – AO system with feedback in the generation mode.

In the generation mode the situation differs completely, it is possible to say that the total passband of the system is near 0.35nm, so the system passband in the generation mode is much narrower than for the same AO filer without feedback.

The comparatively low AO diffraction efficiency of the presented curves *2* and *3* is explained by low power of the acoustic wave aroused in the AO cell.

The proposed AO demultiplexer applies the operation in the generation mode with frequency locking effect used for optical spectrum component selection.

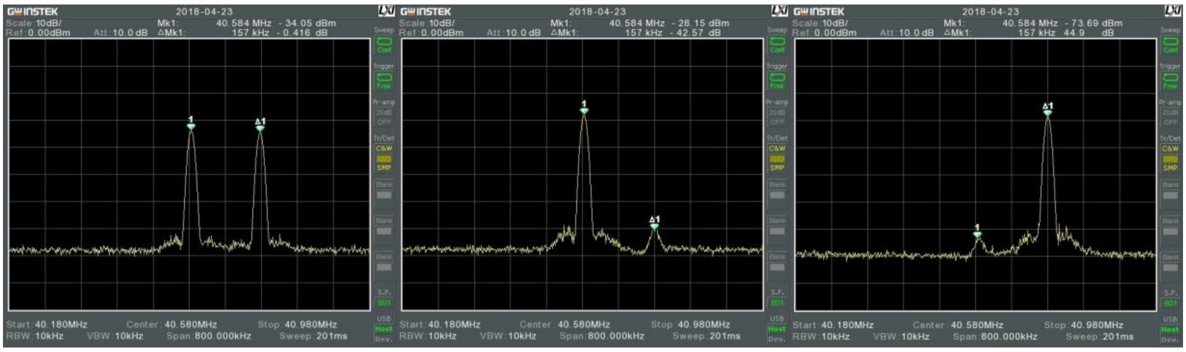
5 THE OPTICAL RADIATION SPECTRUM CONTROL WITH FREQUENCY LOCKING

5.1 Acousto-optic Demultiplexer

The most interesting application of the frequency locking effect is to use it for the creation of the acousto-optic demultiplexer. Let the optical input of the system be fed with radiation containing several discrete spectral components. In the experiment two identical laser modules with a wavelength of radiation near 655 nm were used to simulate such a situation. The radio frequency spectrum analyzer was used to register the spectral composition of the electrical signal in the feedback circuit. The RF signal spectra observed in the feedback circuit with this spectrum analyzer are presented in Fig.3. The laser modules emitted at slightly different wavelengths spaced 2.2 nm apart. Since the intensities of the light beams were practically identical the self-oscillations were excited in the AO system at two frequencies, spaced 157kHz apart (which corresponds to 2.2 nm by Eq. (1)) with almost equal amplitudes (Fig. 3a).

Thus, there are two signals in the electrical circuit and two acoustic waves were excited in the AO cell, on each of which diffracts its own optical wave, and light radiation from both lasers was observed at the optical output of the AO system.

When the external RF generator is connected to the system and tuned to an arbitrary frequency near the AO system self-oscillations frequencies the electrical signal in the feedback circuit will already contain three spectral components - two frequencies of the self-oscillations and one - forced at the frequency of the RF generator. The RF signal power and the feedback gain were selected so that the locking effect bandwidth was less than the self-oscillations frequencies difference. If the frequency of the RF generator was chosen in such a way that self-oscillations were locked at one of the frequencies, then the oscillations at the second frequency were suppressed (Fig. 3b, c). The observed suppression factor was more than 42dB. In this case the optical radiation on the AO system output will contain only at one wavelength



(a) **(b)** **(c)**

Figure 3: The spectra of RF signal in the AO system feedback circuit; (a) – two optical waves on the AO cell input, AO system is in the generation mode; (b) – low frequency self-oscillations are locked; (c) – high frequency self-oscillations are locked.

corresponding to the locked self-oscillation frequency. So this selection of the optical wavelength by locking the RF frequency in the feedback may be considered as the AO time domain demultiplexing.

In the general case, in the presence of a large number of discrete spectral components in the optical signal, the number of selected components will be determined by the RF signal spectrum supplied from the external generator. As it is possible to lock simultaneously several self-oscillation frequencies.

Thus, using the effect of AO system self-oscillations frequency locking it is possible to realize the AO demultiplexer capable selection of one or more spectral components of optical radiation. The minimum spacing between the components that it will be able to select will be determined by the characteristics of the AO filter used (for the calcium molybdate crystal with 4 cm AO interaction length, the spectral interval between the components may be less than 1 nm), the crosstalk attenuation between adjacent channels will exceed 42 dB, the tuning rang corresponds to the AO cell tuning range that is usually not less than one octave.

5.2 System Operation Speed Examination

Operation speed is an important parameter of optoelectronic devices especially for the time-domain demultiplexing devices. The processing speed of this system is primarily determined by the acoustic wave propagation time in the AO cell. The AO filter used in the experiment was fabricated from calcium molybdate with 4cm interaction length and $2.91 \cdot 10^5$ cm/s ultrasound velocity, so it has the time constant $\tau = l/V = 13.7$ µs. The examined AO system operation speed depends on the value of the feedback gain factor κ and its limiting value is τ.

It follows from the evaluations carried with Eq.(12)-(13) that the higher is the gain κ, the faster the system goes to the steady-state operation mode with the constant amplitude of the RF signal in the feedback circuit, acoustic wave in the AO cell and light intensity on the output. Thus, if at κ = 6.7 (with a threshold value κ = 6.35), the self- oscillations establishment time is 410 µs, then if feedback gain increases to κ = 8.9 this time decreases to 69 µs. At the same time, the stationary amplitude of the self-oscillations and consequently the AO diffraction efficiency increases.

The minimum time for the stationary self-oscillations amplitude establishment observed in the experiment was 73 µs. At the same time, the 0.86 diffraction efficiency was achieved for the feedback gain κ = 560 (the maximum possible diffraction efficiency in the AO cell used is 0.92). The further diffraction efficiency increase was limited by the maximum attainable gain of the amplifiers used in the feedback circuit.

6 CONCLUSIONS

The examination of the acousto-optic system combining a collinear filter and a feedback circuit was continued in this paper. The operation of this system in the generation mode and the possibility of system self-oscillations locking effect practical application was studied. A new type of AO device was proposed: an acousto-optic demultiplexer with AO collinear filter as the core element.

It was shown that the total transmission bandwidth of the system combining the collinear AO filter and the feedback circuit in the generation mode is much narrower than the half-width of the transmission function of the same collinear AO filter without feedback (0.35 nm to 0.9 nm).

A prototype of an acousto-optic demultiplexer was considered. This device operates by using the frequency locking of the AO system self-oscillations by an external RF generator signal. It was shown that when one or more of the system self-oscillations frequencies are locked, the remaining frequencies are suppressed, and only those optical radiation wavelengths that correspond to the locked frequencies remain on the optical output of the system. In this case, the experimentally observed crosstalk attenuation between adjacent channels exceeds 42dB. The tuning range of the demultiplexer equals to the tuning range of the AO filter.

It was shown that the operation speed of the examined system is determined by the feedback gain, and its limiting value is equal to the acoustic wave propagation time along the entire AO cell length.

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