Acousto-optic Spectrum Analyzer
The New Type of Optoelectronic Device

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Abstract: The new optoelectronic system combining calcium molybdate collinear acousto-optic cell and positive electronic feedback is proposed and examined both experimentally and theoretically. The feedback signal is formed at the cell output due to the optical heterodyning effect with the use of an unconventional regime of collinear cell operation. It is shown that the feedback circuit parameters enable controlling spectral characteristics of the acousto-optic cell, resulting in enhancing the maximal spectral resolution and the accuracy of optical wavelength determination. This system may be treated as the optical radiation spectrum analyzer, as the spectrum of electric signal in the feedback circuit is related with the light spectrum on the system input.

1 INTRODUCTION

Acousto-optic (AO) interaction is one of the main effects used for optical radiation parameters control and examination. The phase diffraction grating induced inside the AO cell by acoustic waves allows controlling the propagation direction, amplitude, frequency and polarization of an optical wave (Goutzoulis, Pape 1994).

AO systems with feedback is the class of optoelectronic instruments that expand the scope of optical information processing problems that can be solved by AO methods. This type of AO systems is comparatively new and poorly studied. It is known that the introduction of feedback allows to improve characteristics of conventional devices and to create absolutely new devices of laser physics and optical information processing (J. Chrostowski, 1982; Poon, 1989, Balakshy, 1996).

The feedback in these systems is hybrid: an optical signal in one of the diffraction maxima at the AO cell output is transformed by a photodetector into an electrical signal that controls magnitude (Balakshy, 2014) or frequency (Balakshy 1995, Balakshy, 1999) of an acoustic wave excited in the cell. The behaviour of the feedback AO systems is extremely complicated. Diverse oscillations (including harmonic, self-modulation and chaotic ones) can be excited (Balakshy, 2014).

The AO feedback systems have two important features. First, such systems are basically distributed because the time of acoustic wave propagation in the cell is compared with the period of oscillations. Second, these systems are principally nonlinear and the character of nonlinearities affects the system behaviour. The nonlinearities, concerned in the first place with the AO cell, give rise to diversity of regimes, but, at the same time, they complicate the analysis of the systems.

In this paper, an electronic feedback is added to the collinear AO cell fabricated of calcium molybdate crystal ($CaMoO_4$) (Harris et.al., 1970; Balakshy, 2009).

The resulting system is unique and has no analogues among the known AO devices

The theoretical and experimental analysis is carried for this optoelectronic system. It is shown that the positive feedback makes it possible to control the shape of the filter transmission function and to suppers the function side lobes resulting in significant enhancement of the spectral resolution and the accuracy of optical wavelength determination. The examined system may be treated as optical spectrum analyzer.

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2 LIGHT INTENSITY MODULATION

The system operation is based on the effect of light intensity modulation effect, predicted and observed experimentally in (Balakshy, 2009; Balakshy 2012). It was reported there that the special case of collinear AO interaction exists that can provide intensity modulation of the output optical radiation at the frequency of the traveling acoustic wave. This peculiarity gives the possibility to introduce the feedback circuit to feed the AO cell transducer by the modulated signal from photodetector.

The scheme of conventional collinear AO filter is presented at figure 1.

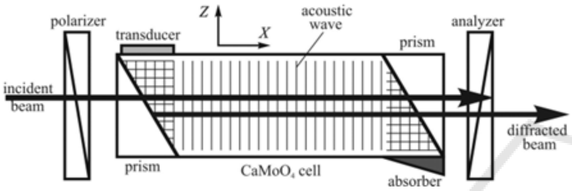


Figure 1: Collinear AO filter scheme.

In the conventional variant of AO collinear filter (Harris et.al., 1970; Balakshy, 2009), polarization of the incident light is set in accordance with the crystal eigenmode polarizations (polarization angle α is equal to 90° or 0° with regard to the Y axis). In the process of AO interaction, the light polarization changes to the orthogonal one (anisotropic diffraction). Therefore, crossed analyzer (polarization angle α is equal to 90° or 0°, respectively) let pass only the diffracted optical radiation.

The transmission function of the filter used in the experimental setup is presented at figure 2, the filter passband equals 0.9nm in this case.

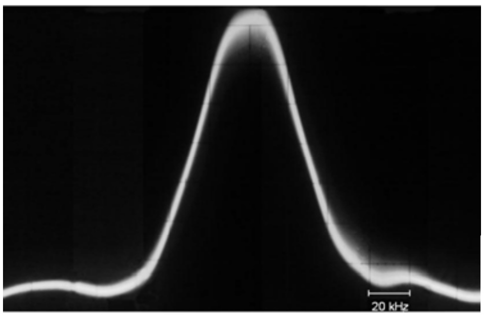


Figure 2: Transmission function of conventional collinear AO filter.

Quite another situation appears in the special case, when the incident optical wave has polarization which differs from the eigenmode polarizations. In this case, the wave, entering the AO cell, is split into two waves with amplitudes E_i^Y (ordinary mode) and E_i^Z (extraordinary mode) which are polarized along the Y and Z crystallographic axes. These waves diffract in the acoustic field independently and with equal efficiency. The ordinary wave E_i^Y is scattered into the +1st diffraction order, forming the waves E_0^Y (the zeroth order with ordinary polarization) and E_{+1}^Z (the +1st order with extraordinary polarization). The extraordinary optical wave E_i^Z diffracts in a similar manner into –1st order, forming the waves E_0^Z and E_{-1}^Y. The optical waves of the zeroth order E_0^Y and E_0^Z have the frequency ω equal to the frequency of the incident light, whereas the waves E_{+1}^Z and E_{-1}^Y have frequencies ω+Ω and ω-Ω , respectively.

The analyzer oriented at the angle β let pass through only a part of the light components. The beatings of the components with frequency shift and unshifted components result in the modulation of output light intensity with ultrasound frequency. The light intensity on the system output may be written as the sum of three components:

$$I_d = |(E_0^Y + E_{-1}^Y)\cos\beta + (E_0^Z + E_{+1}^Z)\sin\beta|^2 \quad (1)$$

$$I_d = I_0 + I_1\cos(\Omega t + \varphi_1 + \Phi) + I_2\cos(2\Omega t + \varphi_2 + 2\Phi) \quad (2)$$

Amplitudes of I_1 and I_2 components depend on the polarizer and analyzer orientations. The I_1 component has intensity modulation with ultrasound frequency aroused in the AO cell. That is why it may be used to feed the AO cell transducer with feedback circuit. The magnitude of this component is described by equation:

$$I_1 = I_i\frac{\Gamma}{A}\sin\left(\frac{\sqrt{A}}{2}\right)\cdot\sqrt{\Gamma^2\cos^2\left(\frac{\sqrt{A}}{2}\right) + R^2} \quad (3)$$

where $A = \Gamma^2 + R^2$, Γ is the Raman-Nath parameter (AO coupling coefficient) which is proportional to the acoustic wave amplitude and $R = (2\pi l/V)(f - f_c)$ is the dimensionless phase mismatch [1]. In the last equation l is the AO interaction length, f – ultrasound frequency, f_c is the phase matching frequency for the given optical wavelength, V is the acoustic wave velocity along X crystallographic axis. The AO filter transmission function for I_1 component is presented at figure 3.

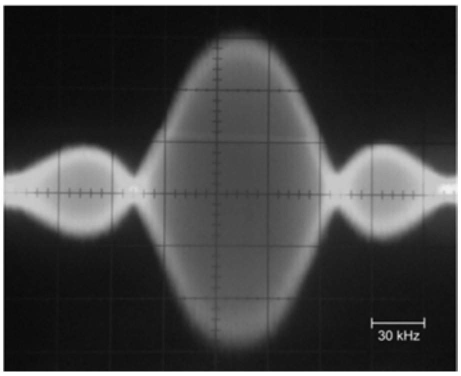


Figure 3: AO collinear filter transmission function for I_1 component.

It is possible to see the intensity modulation with Ω frequency. Also the shape of transmission function differs from the conventional one. It has flat top, higher side lobes and wider passband (1.5nm at 3dB level).

3 FEEDBACK INFLUENCE

The existence of I_1 component modulated with ultrasound frequency makes it possible to introduce feedback circuit (figure 4) (Balakshy et.al., 2016, Mantsevich et.al. 2016).

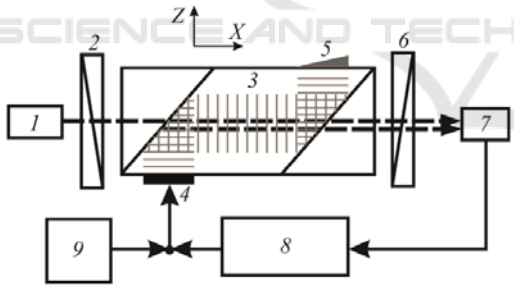


Figure 4: AO spectrum analyzer scheme.

An optical beam from laser *1* passes through polarizer *2* and enters collinear AO cell *3*. A longitudinal acoustic wave is excited in the cell by piezoelectric transducer *4* and after the reflection propagates along X axis. The light beam passes through the cell along the X axis as well. The regime of travelling acoustic waves is ensured by acoustic absorber *5*. The diffracted radiation was registered by photodetector *7* and its output signal at the frequency f was sent through feedback *8* to the transducer together with the signal of HF generator *9*. The feedback circuit had tuneable gain factor to 30dB and phase shifter which provided phase tuning to an optimal meaning. The spectrum of electric signal in the feedback circuit is defined by the optical spectrum on the AO cell input and may be registered by the RF spectrum analyzer.

The feedback appearance changes dramatically the shape of transmission function presented at figure 2. Also tuning the circuit gain factor it is possible to control the shape and passband of the system transmission function. One of the transmission functions obtained in the experiment is presented at figure 5.

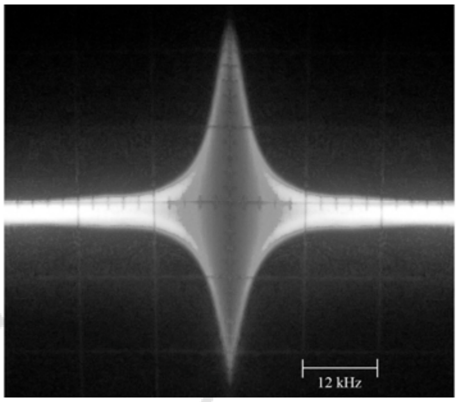


Figure 5: AO filter transmission function with feedback.

The transmission function side lobes disappeared and the transmission band δf noticeably narrowed. The sharpening of the spectral characteristic occurs because the feedback coefficient is proportional to the photodetector signal amplitude. For the oscillogram presented in figure 5, $\delta f = 4.8$ kHz, $\delta\lambda = 0.075$ nm and contrast $\kappa = 60$ (κ is a ratio of the transmission coefficient at the characteristic maximum to the transmission in the first side lobe). Thus, the narrowing of the AO filtration band is as great as 20 times, that corresponds to the same increasing the accuracy of the optical wavelength measurement. In our experiments, the maximal narrowing δf ranged up to approximately 40 times.

4 THEORETICAL MODEL

Considering the second section of the paper and fig. 4 it is possible to write the following equation describing the photodetector 7 output signal at Ω frequency (Balakshy et.al., 2016, Mantsevich et.al. 2016).

$$U_\Omega(t) = \sigma I_1(t) = \sigma I_1 \cos(\Omega t + \varphi_1), \qquad (4)$$

where σ is the detector sensitivity. The voltage at the AO cell transducer may be written in the form

$$\mathrm{U_T(t) = U_G \sin\Omega t + \sigma\mu I_1 \cos(\Omega t + \varphi_1 + \chi)} \\ = \left(\Gamma_g + \Gamma_f\right)/\gamma, \tag{5}$$

if the feedback circuit has the amplification coefficient μ. In equation (5) U_G is the HF generator signal magnitude, χ is the phase shift in the phase shifter and γ is the transducer conversion factor.

The conditions of phase equation (6) and magnitude balance equation (7) for the examined system are the following:

$$\Omega t + atan\left[\frac{\sqrt{A}}{R} cot\left(\frac{\sqrt{A}}{2}\right)\right] + \chi = 2\pi n \tag{6}$$

$$I_i \frac{\sigma\mu\gamma}{4} sinc\left(\frac{\sqrt{A}}{2\pi}\right) \cdot \\ \cdot \sqrt{4\cos^2\left(\frac{\sqrt{A}}{2}\right) + R^2 sinc^2\left(\frac{\sqrt{A}}{2\pi}\right)} = 1 \tag{7}$$

where $A = \Gamma^2 + R^2$ is like in the equation (3). Equations (6) and (7) form the nonlinear system relatively to the variables Γ (normalized magnitude of ultrasound signal) and R (normalized ultrasound frequency). The solution of this system of equations permits to analyze the behavior and characteristics of the examined optoelectronic system.

4.1 Transmission functions simulation

We will examine the influence of feedback circuit on the collinear AO filter spectral characteristics in this part of the paper. The transmission functions are calculated by substitution into equation (3) the values of Γ and R parameters obtained from numerical solution of equations (6) and (7) system. The equation (5) gives the transmission function shape, defining the AO diffraction efficiency, spectral passband and contrast.

We assume that the optical wavelength of incident radiation is 655nm, the AO interaction length in the cell is 4 cm, the detector sensitivity is $\sigma = 0.7$, the transducer conversion factor $\gamma = 0.9$ (such parameters meet the characteristics of the experimental set up).

The transmission functions $I_1(R)$ simulations for various values of feedback circuit gain μ and generator signal magnitude defined by Raman-Nath parameter Γ_g were carried at first. The results of computations are presented at figure 6a,b.

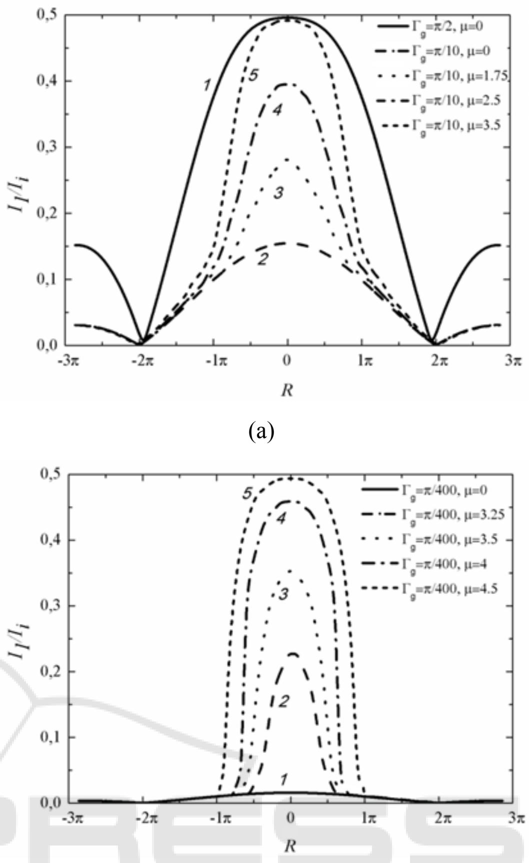


Figure 6: AO collinear cell with feedback circuit transmission functions. a – Raman-Nath parameter $\Gamma_g = \pi/10$. b - $\Gamma_g = \pi/400$.

Figure 6 represents transmission functions of collinear AO cell simulated for various feedback gain μ (it should be noted that the value of gain coefficient μ is normalized and didn't match with experimental one) for two Ramam-Nath parameters $\Gamma_g = \pi/10$ (figure 6a) and $\Gamma_g = \pi/400$ (figure 6b). Such magnitudes of Γ_g indicate that the acoustic power from generator is lower in 100 and $16 \cdot 10^4$ times correspondingly than needed to obtain maximal diffraction efficiency at the traditional case of collinear AO cell running without feedback.

The following conclusions can be drawn after examining the dependences at figure 6. Firstly, increasing the feedback gain it is possible to achieve maximal diffraction efficiency for arbitrary value of Γ_g parameter. Secondly, the magnitude of system with feedback transmission function side lobes is determined by the magnitude of AO collinear cell transmission function without feedback obtained for the same Γ_g parameter (curve *2* at figure 6a and curve *1* at figure 6b). Thus, reducing Γ_g and simultaneously increasing μ the spectral contrast κ can be improved. For example, $\kappa = 14.5$ for curve *5* at figure 6a, this vale significantly exceeds spectral contrast of conventional collinear filter. Spectral contrast equals 145 for the curve *5* at figure 6b and this value is higher than values ever mentioned in literature (Mazur et.al., 1996). Thirdly, comparing various curves at figure 6 we may conclude that for every Γ_g value exists optimal gain value that provides minimal passband of the system.

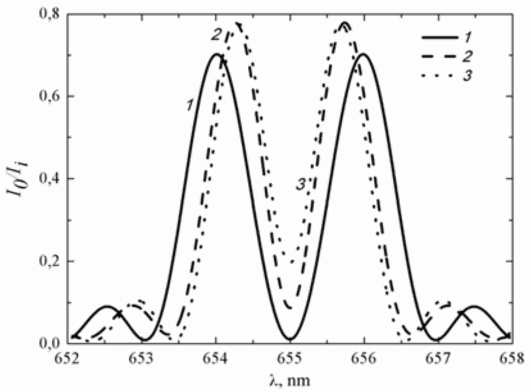
Maximal AO diffraction efficiency $\zeta = I_1/I_i$ reduce with the decrease of system passband. The passband of transmission function *3* at figure 6a is in 1.3 times less than for the conventional collinear AO filter with the same interaction length but with diffraction efficiency near 56%. For the curve *2* at figure 6b passband is in 3.5 times narrower than for the collinear AO filter without feedback but the diffraction efficiency will be about 46%.

Our simulations have shown that 0.05nm passband may be achieved, but the diffraction efficiency in this case reduces to 6%. The passband of the curve 5 at figure 6b is 20% narrower than for the traditional collinear AO filter with the same AO interaction length but the diffraction efficiency is still maximal and spectral contrast $\kappa = 145$. These parameters indicate that system with feedback has great advantages for spectroscopic applications.

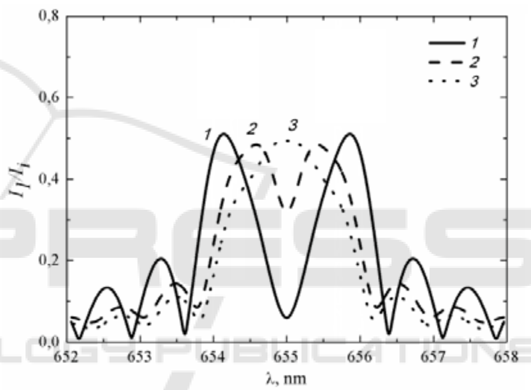
4.2 Spectral resolution determination

Let's pretend that the optical radiation containing two optical wavelengths λ_1 and λ_2 passes through the examined system. We will simulate the spectral dependences of optical signal on the output of AO cell for such incident radiation for the following cases: collinear AO filter in traditional geometry (figure 7a) (Harris et.al.,1970), collinear AO filter with special orientation of polarizer and analyzer (figure 7b) without feedback (Balakshy,Mantsevich, 2009) and our system containing collinear AO cell and feedback (figure 7c). Three curves were calculated for each case for three pairs of optical wavelengths: curve *1* - λ_1=654 nm, λ_2=656 nm, $\Delta\lambda$= 2 nm; curve *2* - λ_1=654.25 nm, , λ_2=655.75 nm, $\Delta\lambda$=1.5 nm; curve *3* - λ_1=654.335 nm, λ_2=655.665 nm, $\Delta\lambda$=1.33 nm.

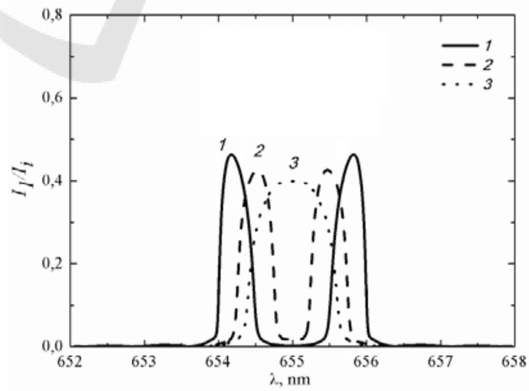
Figure 7a represents the dependence of diffracted light intensity on optical wavelength for the conventional collinear AO filter. These curves have two main maxima that correspond to the incident optical radiation wavelengths. The examined collinear AO filter with 4cm AO interaction length resolve light spectrum components well for all three cases but it doesn't provide high spectral contrast. The transmission functions intersect at levels 1.5%, 11,1% and 25.5% from maximal value for curves



(a)



(b)



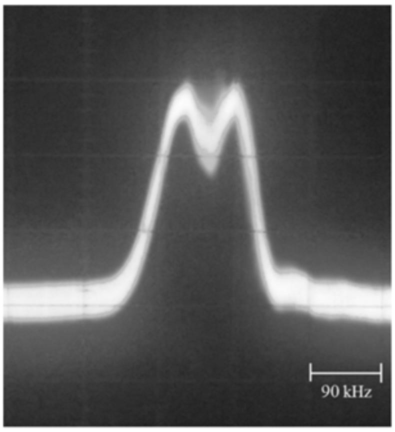
(c)

Figure 7: AO collinear cell spectral response on incident light with two spectral components. a – conventional AO cell; b - AO cell with specific polarizer orientation; c – AO cell with feedback, $\Gamma_g = \pi/200$, $\mu = 4$. curve *1* - $\Delta\lambda$=2 nm; curve *2* - $\Delta\lambda$=1.5 nm; curve *3* - $\Delta\lambda$=1.33 nm.

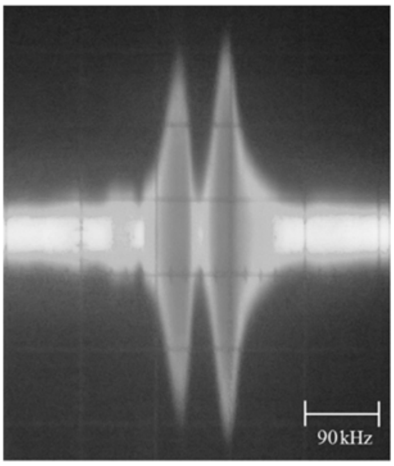
1-3 correspondingly (central minimum of the dependences). If we simulate the same dependences for the same AO cell but with special polarizer and analyzer orientation the significant differences could be observed. Firstly, the spectral contrast is worse than for conventional collinear AO filter. Secondly, the deterioration of spectral resolution occurs, the value $\Delta\lambda = 1.33$ (curve *3* at figure 7b) is marginal for this case.

The situation changes significantly if we introduce the feedback circuit. The results of calculations for the collinear AO cell with feedback ($\Gamma_g = \pi/200$, $\mu = 4$) are presented at figure 7c. The side lobes of transmission function are suppressed hence the spectral contrast increases in comparison with the traditional geometry. Transmission functions overlap at the level 0.4% and 4% from maximal for curves *1* and *2* correspondingly. It is possible to enhance the spectral contrast by reducing Γ_g and increasing μ values. Nevertheless the spectral resolution of the system decreases, it will be set by the dependences at figure 7b as exactly these curves are transformed under the action of the feedback. That is why the system is not able to select two spectral lines separated by spectral interval $\Delta\lambda = 1.33$ nm (curve *3*). But the spectral lines displaced at wider intervals $\Delta\lambda$ will be selected well without overlapping.

The theoretical simulations presented at figure 7 were verified in experiment. The results of the experimental investigation are presented at figure 8. Here the spectral response of the conventional collinear AO filter (figure 8a) and AO system with feedback (figure 8b) for the optical radiation (near 655nm) containing two components with spectral interval $\Delta\lambda = 1.4$ nm are presented. Both figures have the same scale.



(a)



(b)

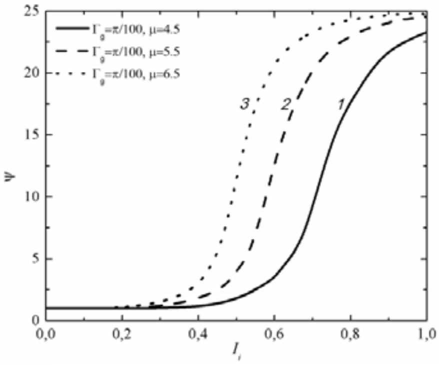
Figure 8: AO collinear cell spectral response for incident optical radiation with two spectral components.
a – conventional AO cell; b – AO cell with feedback, $\Delta\lambda = 1.4$ nm.

The deviation of diffracted light intensity in the centre of the conventional collinear AO filter spectral response curve is approximately 15%. The feedback appearance strongly sharpens the spectral response of the system and the spectral components became clearly distinguishable.

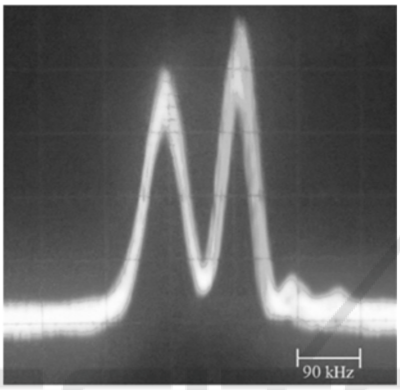
4.3 Nonlinear effects in the system

The examined optoelectronic system, as the most part of the electronic systems with feedback, is nonlinear. The nonlinearity is one of the main constraints and appears as the diffraction efficiency dependence on the incident optical radiation intensity I_i in this case.

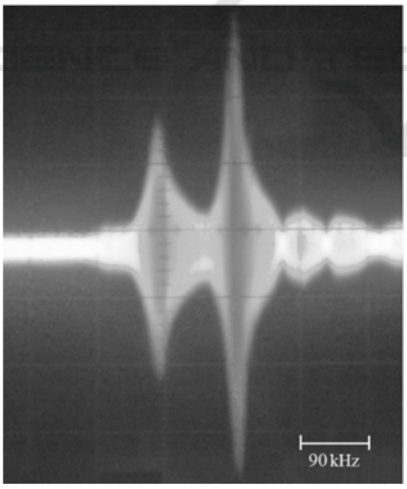
The nonlinearity causes the distortion of system spectral response, when optical spectral components pass through the system with varied amplification. Let's define the coefficient of diffraction efficiency amplification ψ as the ratio of diffraction efficiency for the system with feedback to the diffraction efficiency I_1/I_i without feedback. The results of $\psi(I_i)$ evaluations for the HF generator acoustic power $\Gamma_g = \pi/100$ and various feedback circuit amplification values are presented at figure 9. These dependences have evidently nonlinear shape. The growth of feedback circuit amplification μ causes the shift of $\psi(I_i)$ dependences to the left and nonlinearity may appear for lower values of incident light intensity. The magnitude of diffraction efficiency amplification is in the range between 1 and 25 for $\Gamma_g = \pi/100$, this mean that some spectral components of light will pass through the system



(a)



(b)



(c)

Figure 9: AO collinear cell with feedback nonlinearity. a - diffraction efficiency amplification $\psi(I_i)$ evaluations, $\Gamma_g = \pi/100$, $\lambda = 655$ nm; curve *1* - $\mu = 4.5$, curve *2* - $\mu = 5.5$, curve *3* - $\mu = 6.5$; b - experimentally measured conventional collinear AO filter spectral response; c – experimentally measured collinear AO filter with feedback spectral response

without any amplification and some other will be amplified in 25 times.

The experimental verification of nonlinearity existence was carried in the following way. Optical radiation containing two spectral components with diverse intensity (20% difference) is applied to the system optical input. The spectral response on such signal was registered by conventional AO filter (figure 9b, AO filter is the linear system by light) and by the system with feedback (figure 9c). Comparing the oscillograms figures 9b and 9c it can be seen that the difference between diffracted radiation intensities is much lower for the conventional AO filter (20% difference) than for the AO system with feedback (46% difference).

4.4 The continuous input optical spectrum case

The examined AO system nonlinearity has both positive and negative influence. On one hand the nonlinearity disturbs the spectral response of the system, and on the other hand it enhances the light spectrum contrast.

AO tunable filters are widely used for spectral analysis to date (Mazur et.al, 1996; Mantsevich et.al., 2015). In this application the incident light has continuous spectrum with some peculiarities, for example, absorption bands of gases.

Let's treat the case when incident optical radiation has continuous spectrum $I_i(\lambda)$ shown by curve *1* at figure 10.

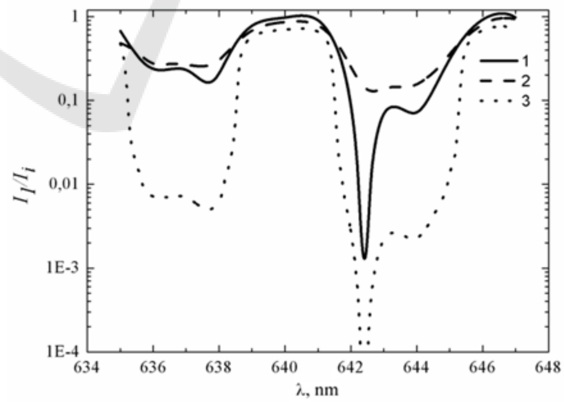


Figure 10: AO optical spectrum analyzer operation. Curve *1* – spectrum on the input $I_i(\lambda)$, curve *2* – light spectrum on the output of conventional collinear AO filter $\Gamma = \pi$, curve *3* – light spectrum on the output of AO system with feedback $\Gamma_g = \pi/100$, $\mu = 5.5$.

It is possible to simulate the spectrum of optical radiation on the output of conventional collinear AO filter (curve *2* figure 10) and on the output of collinear AO cell with feedback (curve *3* figure 10), for the curve *3* the parameters AO interaction parameters were: $\Gamma_g = \pi/100$, $\mu = 5.5$.

Curve *2* differs much from the curve *1*. The reason of this difference is that the conventional collinear AO filter transmission function has side lobes that let pass the undesirable spectral components and cause the smoothing of diffracted light spectrum peculiarities and significantly distort its shape.

Thereby the real spectral resolution of the AO filter is much lower than the filter transmission function passband (approximately in 10 times).

If we use the AO system with feedback the high spectral contrast gives the possibility to dispose the side lobes and to let pass only the spectral components that fit the passband. Consequently the shape of curve *3* at figure 10 is much closer to the shape of curve *1*, except the spectrum contrast. The growth of light spectrum contrast is caused by the AO system nonlinearity, but this distortion could be corrected using the dependences presented at figure 9 and calibrations.

5 CONCLUSIONS

In this paper, we have analyzed the functioning of the optoelectronic system containing the collinear AO filter and electronic feedback. This feedback is implemented due to a special geometry of AO interaction in the collinear cell, when light diffraction by a traveling acoustic wave is accompanied by light intensity modulation at the acoustic frequency *f*. Due to this peculiarity, the output signal of the photodetector contains the component that could feed the cell transducer together with the RF generator. The feedback action results in narrowing the system spectral passband and, consequently, increasing the accuracy of optical wavelength measurement. The main advantage of the examined system is that the shape of the filter transmission function can be controlled through the gain factor of the feedback amplifier. It can be used for conversion of the optical spectrum into the electrical one.

The system spectral resolution is limited by the AO collinear filter passband without feedback.

The examined system may be considered as a new type of spectrum analyzer but with taking into consideration the feedback nonlinearity. This nonlinearity can be taken into account at computer processing of the output signal and calibrations.

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