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Filtration of images in acoustic and optics

EKPEKPO, A

Department of Physics,Delta State University, Abraka

ABSTRACT

Some aspects of tunable acousto-optic filters performance are considered and applications to optical image filtration devices are described in this paper. Among various types of acousto-optic devices, tunable acousto-optic filters seem to be very attractive. As compared with spectral devices of other classes acousto-optic filters appear superior because of the following advantages; Universality, relative simplicity in construction and reliability. The spectral bandwidth of acousto-optic filters $\Delta\lambda$ in the visible region is no more than $\Delta\lambda < 0, I_{nm}$ while the resolution $R= \lambda/\Delta\lambda$ can exceed the value $R = 10^3$. The transmission coefficient of a filter is determined as a light flux transmitted by the filter divided by light incident on the device. Transmission T may be done close to T= 100%.

INTRODUCTION

The physical principle of acousto-optic filter operation is based on Bragg diffraction on ultrasound phenomenon selectivity. It is known that in case of an acoustic wave propagation through isotropic medium coherent (non-diffusive) scattering of light on ultrasound occurs, if some special conditions are satisfied [1, 2]. Scattering of light on ultrasound is usually treated as photon phonon-interaction for which conservation laws of energy and momentum are valid.

$$\omega_d = \omega_i \pm \Omega \qquad (1)$$

$$\vec{k}_d = \vec{k}_i \pm \vec{k} \qquad (2)$$

where ω_i and ω_d – are frequencies of incident and diffracted light Ω angular frequency of ultrasound k_i and k_d –wave vectors of incident and diffracted beams, $\vec{k}$ –wave vector of an acoustic beam, light and sound beams configuration is an isotropic acousto-optic cell and wave vector diagram corresponding to equation (2) are shown in fig. 1a and fig. 1b.

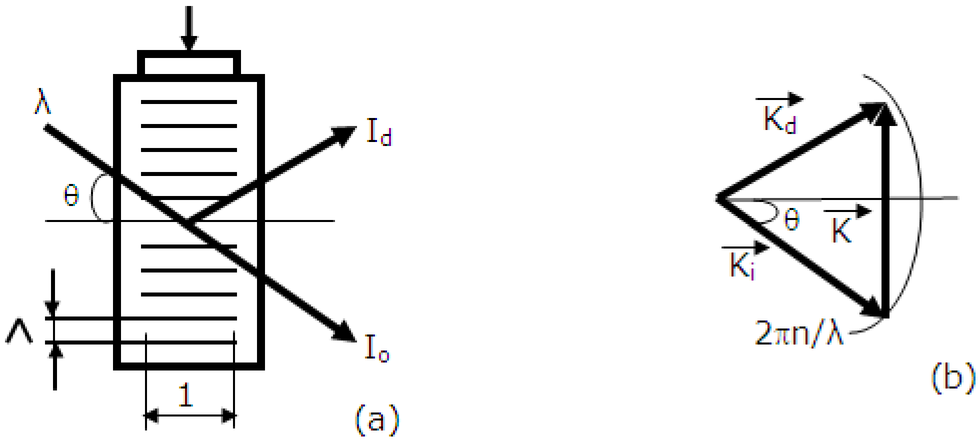

Fig 1. Bragg interaction in an isotropic medium (a) and a wave vector diagram (b)

From equation (2) Braggs condition is derived which couples wavelength of light λ, angle of incidence θ and ultrasound wavelength Λ

$$\sin\theta = \lambda/2n\Lambda = \lambda f/2nV \tag{3}$$

where n = index of refraction of the medium.

In case of a light beam with a continuous spectrum incident upon an acousto-optic cell (angle of incidence and acoustic frequency f are fixed), only a very narrow band of light wavelength will be diffracted by ultra sound due to the selectivity of a Bragg diffraction process.

$$\lambda = 2nV\sin\theta/f \tag{4}$$

In general, the statement presented here is based on a conception of plane acoustic and optic waves. In real devices the waves are not plane due to the fact that linear dimensions of beams are limited. It is shown in fig. 1a that the size of the acoustic column is 1. So the acoustic beam is characterized by an angle of divergence $\Delta\theta_s = v/fl$ as shown in fig. 2a [1, 2].

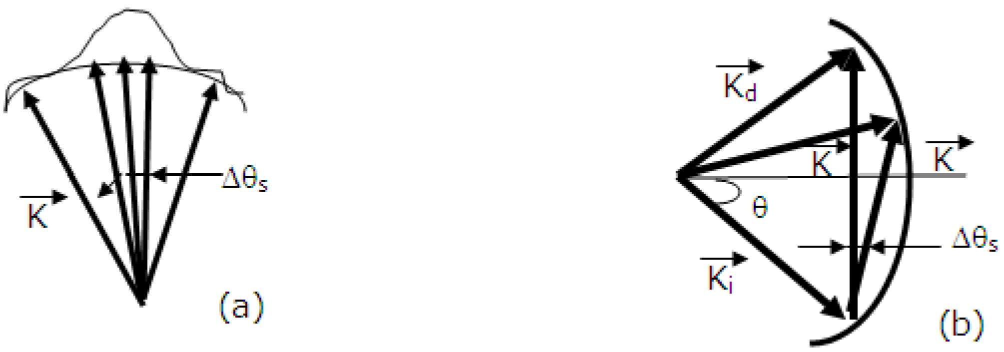

Fig. 2 Angular divergence of ultrasound (a) and a wave vector diagram (b)

Vector diagram corresponding to fig. 1a is shown in fig. 2b. As a result a collimated light beam with a wavelength λ will be diffracted in a band of acoustic frequencies Δf which is proportional to

$$\Delta f = 2nV\cos\theta\,\Delta\theta_s/\lambda \tag{5}$$

where $\Delta\theta_s = v/fl$. The condition of Bragg diffraction selectivity due to angular divergence of an acoustic beam is distorted here. The distortion of selectivity will take place due to angular divergence of a light beam too. Angular divergence of a light beam with a linear aperture a is $\Delta\theta_L = \lambda/a$.

It is evident that in case of a light beam with a continuous spectrum of optical frequencies angular divergence of light $\Delta\theta_L$, as well as ultrasound will provide diffraction in a spectral bandwidth.

$$\Delta\lambda = 2nV\cos\theta\, \Delta\theta_L/f \qquad (6)$$

THEORETICAL CONSIDERATION AND CALCULATIONS

Calculations performed using equation (6) showed that high spectral resolution R may be achieved in isotropic media at very high and not convenient in practice acoustic frequencies f when cost→0. Angular apertures requirements of light beams are severe due to the fact there is a linear increase of the bandwidth $\Delta\lambda$ of equation (6) with $\Delta\theta_L$ or $\Delta\theta_s$. This is why the filtration of optical images with high spectral and spatial resolution using isotropic light diffraction is impossible.

Great abilities taking into the consideration acousto-optic filtration, in comparison with isotropic diffraction possess acousto-optic interactions in an isotropic media-optical crystal [6]. Vector diagram for acousto-optic interaction in a uniaxial crystal is shown in fig. 3.

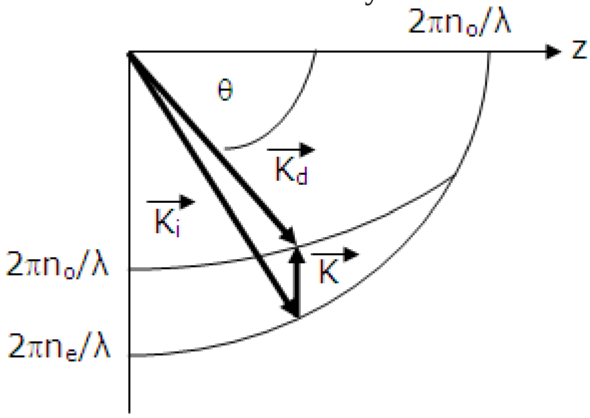

Fig. 3 Anisotropic interaction corresponding to non-collinear filtration of light

Wave vector of ultrasound $\vec{k}$ is orthogonal to the optic axis

$$\lambda = \Delta nV\sin\theta/f \qquad (7)$$

where $\Delta n = n_e - n_o$ –birefringeness of the crystals used n_o and n_e ordinary and extraordinary indexes of refraction. Relatively narrow spectral bandwidth $\Delta\lambda$ of the filter based on anisotropic diffraction.

$$\Delta\lambda = \Delta nV\cos\theta\, \Delta\theta/f \qquad (8)$$

is achieved at convenient acoustic frequencies $f = 10^7 – 10^8$ Hz[3, 4]. However it is clear that the spectral resolution R and the bandwidth $\Delta\lambda$ of equation (8) are characterized by a linear increase with optical angular aperture $\Delta\theta$ of a light beam, if $\theta < \pi/2$. This is why the geometry examined does not allow efficient filtration with high spectral resolution of light beams incident on the acoustic-optic cell at different angles θ [9]. Optical image filtration in such a case as well as in isotropic medium is impossible.

Spectral bandwidth of equation (8) decreases with approaching collinear diffraction [5, 6], if $\theta < \pi/2$. Vector diagram of collinear diffraction is shown in fig. 4a. Frequency dependence of the angle of incidence is presented in fig. 4b for the case of light wavelength λ fixed.

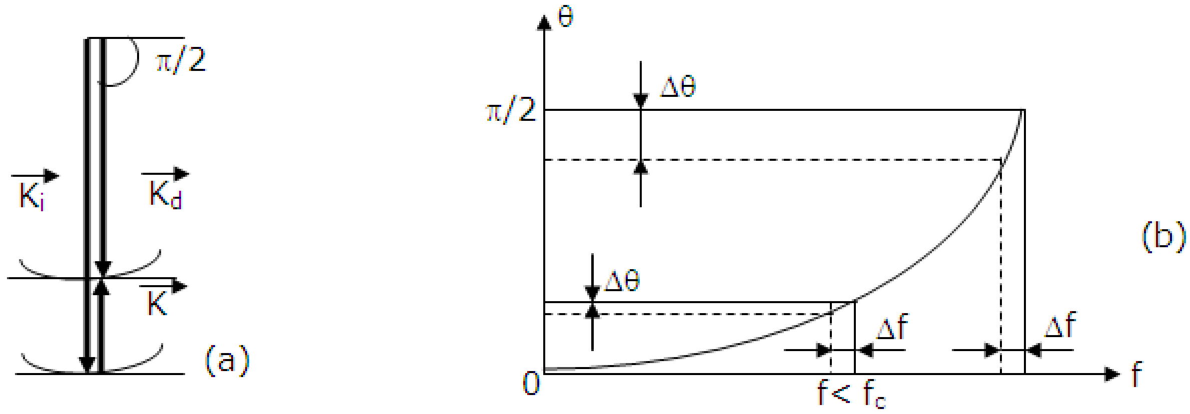

Fig. 4 Vector diagram (a) and frequency dependence of angle of incidence (b)

Frequency dependence $\theta(f)$ corresponds to the diagram in fig. 3 and fig. 4a. Figure 4b shows that the derivative $d\theta/df \to \infty$, if $\theta < \pi/2$. As a result small changes of acoustic frequency Δf are accompanied by considerable changes of angle of incidence Δf. However the same changes of frequency of correspond to $\Delta\theta \to 0$, if $f \to f_c$ and the interaction is far from collinear. There is an approximate relationship

$$\Delta\lambda = \lambda\Delta f/f \quad (9)$$

The same angular divergences Δθ correspond to different frequency bands Δf. The frequency band $\Delta f \to 0$, if $d\theta/df \to \infty$. In this case spectral bandwidth $\Delta f \to 0$. Vertical part if the curve $\theta(f)$ corresponds to vector diagram fig. 4 with parallel tangent lines to the ends of $\vec{k}_i$ and $\vec{k}_d$ vectors. That is why the bandwidth Δλ does not depend on angular divergences of light and sound beams in first approximation. It depends on interaction length of optical and ultrasound waves. The highest spectral resolution R is achieved in collinear filters. Spectral bandwidth of filters can be made $\Delta\lambda < 0$. I_{nm} Limiting resolution of collinear filters is defined by such effects as altenuation of ultrasound and acoustic power density decrease due to divergency of ultrasound [7].

Collinear filters provide performance with light beams with angular apertures of a few degrees. This is an advantage in comparison with non-collinear devices. However in practice collinear diffraction in the majority of known effective anisotropic crystals is not observed. Besides, the construction of collinear filters appears to be more complicated [8].

The advantages of collinear diffraction are possible to combine with the opportunities of non-collinear diffraction if the interaction geometry is chosen like in fig. 5.

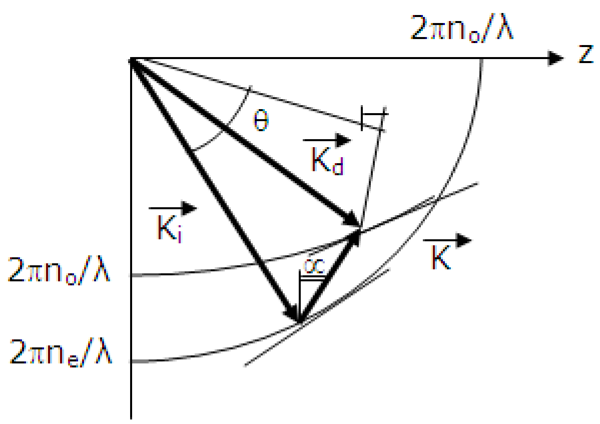

Fig. 5 Wave vector diagram of large angular non-collinear filtration

Wave vector of ultrasound $\vec{k}$, unlike the geometry of diffraction in fig. 3, forms with the perpendicular to the optical axis an angle $0 < \propto \leq \propto_{max}$ [1]. Frequency dependence of the angle of light on ultrasound is shown in fig. 6.

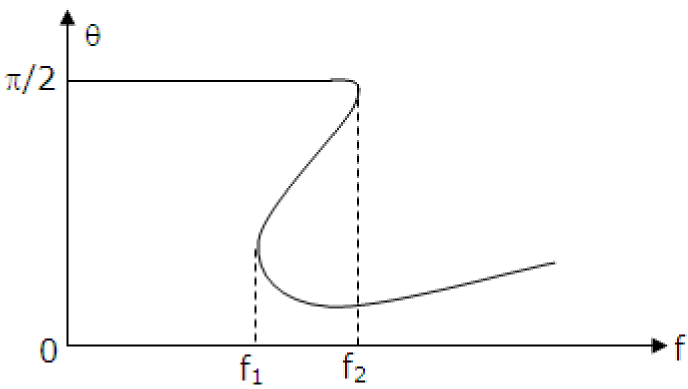

Fig. 6. Frequency dependence of incidence angle for large angular filtrations

It can be seen that the geometry of interaction is characterized at frequencies f_1 and f_2 by two sections of θ(f) curve where $d\theta/df \rightarrow \infty$. It is evident that the spectral bandwidth of the devices in the first approximation does not depend upon the divergency of a light beam, as it takes place in a collinear filter. The lines tangent to the ends of $\vec{k}_i$ and $\vec{k}_d$ vectors are parallel. It provides the filtration of light beams with angular apertures more than ten degrees and design of an acousto-optic device for optical image filtration with high spectral and spectral resolution.

A relation can be found from vector diagram fig. 5 between the angle of incidence θ, optical wavelength λ and a acoustic frequency f [3].

$$\lambda = (^{V}/_{f}) \left[n_i \sin\theta - (n_o^2 - n_i^2 \cos^2\theta)^{1/2}\right] \quad (10)$$

where

$$n_i = n_e n_o \left[n_e^2 \cos^2(\theta + \propto) + n_o^2 \sin^2(\theta + \propto)\right]^{-1/2} \quad (11)$$

With the help of equation (10) for λ = constant, it is possible to calculate a family of curves θ(f) where ∝ is a parameter.

The dependence θ(*f*) are shown in fig. 7.

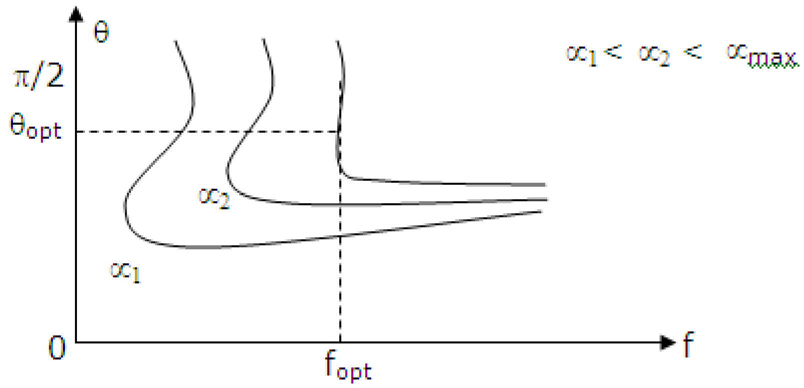

Fig 7 A family of frequency dependence curves of light incidence angles

Analysis show that in designing a filter geometry of interaction is to be chosen corresponding to greater value of angles of incidence and higher acoustic frequencies, other conditions being equal. However, the optimum case of diffraction suitable for large angular apertures filtration is the case $\propto = \propto_{max}$. The spectral bandwidth Δλ depends on angular divergence as $\Delta\lambda \sim (\Delta\theta)^3$, if $\propto = \propto_{max}$ and $\theta = \theta_{opt}$. The angular aperture of an optimum non-collinear acousto-optic filter can be done in the order of 20° - 40° [1, 2]. It should be mentioned that the optimum tilt of k vector usually is $\propto_{max} \sim 19°$. The angle of incidence is approximately equal to $\theta_{opt} \sim 36°$.

RESULTS AND DISCUSSION

Experimental investigation of optical images filtration was formed using an acousto-optic filter on TeO_2 crystal. Paratellurite is a particularly attractive material for the acousto-optic medium since it has a very high figure of merit [1]. High value of the figure of merit corresponds to low drive electric power requirements. The acoustic-optic interaction plane includes [001] and [110] directions in the crystal. Wave vector of ultrasound $\vec{K}$ has a tilt angel $\propto = 10°$ with the direction [110] in the crystal. An acousto-optic filter to be examined in this paper uses geometry of interaction (fig. 8) based on $\propto = 10°$.

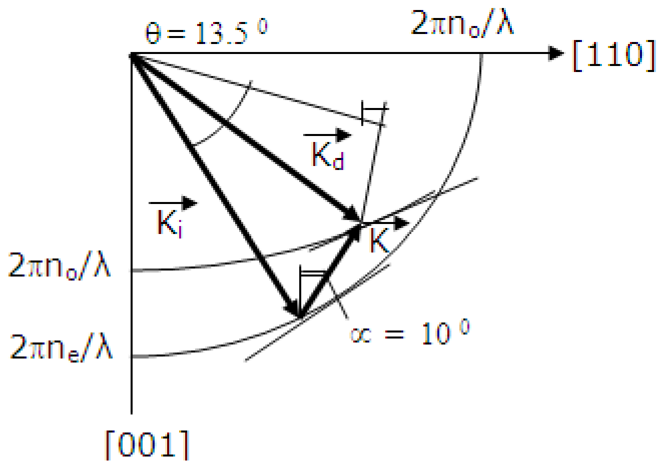

Fig. 8 Wave vector diagram of interaction in paretellurite single crystal

A single of crystal of paratellurite is used as a medium of light and sound interaction. A shear acoustic wave is generated by a X-cut $LiNbo_3$ transducer as it is shown in (fig. 9).

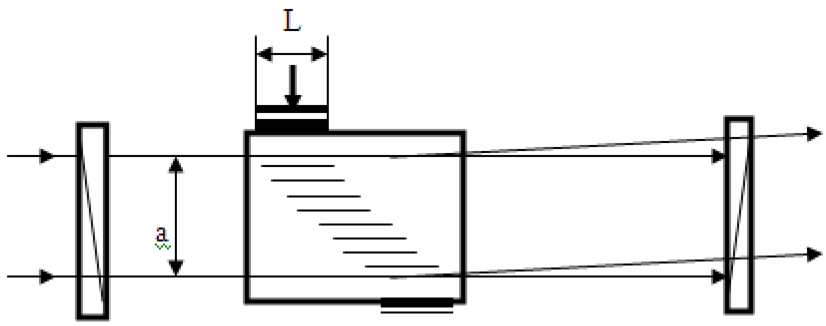

Fig. 9 Schematic diagram of the acousto-optic paratellurite filter

The dimensions of a transducer are L= 0.25cm and D= o.3cm. The dimension D is in the orthogonal direction. The linear aperture of the filter (the dimensions of an acoustic column) is a = 0.5cm and d= 0.3cm. Incident optic beam as extraordinary polarized, the diffracted light beam has an ordinary polarization.

Preliminary measurement of acousto-optic cell parameters was performed with the help of a He-Ne Laser beam at a wavelength λ= 633nm. Laser beam probing of the acoustic column showed that the transducer generated shear waves in the crystal in the frequency band *f*= 110 – 190MHz. Relative changes of acoustic power P_a with frequency *f* are shown in fig. 10a.

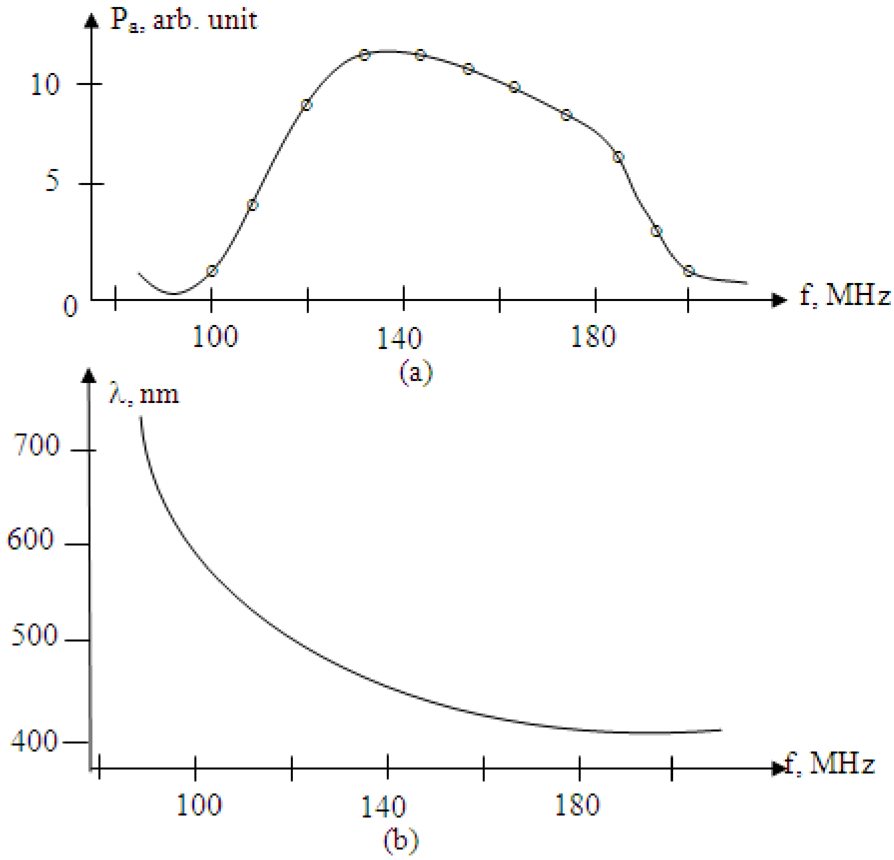

Fig. 10 frequency dependence of the acoustic power (a) and the tuning curve (b)

Tuning curve is presented in fig. 10b. It can be seen that tuning of the device all over the visible spectrum of light is achieved by changing ultrasound frequency in a band *f*= 110 – 90MHz. Electric drive power P= 1.0W provides the diffraction efficiency Id/Io = 0.5 and transmission coefficient T= 50%. Frequency dependence of the angle of incidence was calculated for λ = 633nm using equation (10). The relationship $\theta(f)$ in TeO_2 crystal is shown in fig. 11.

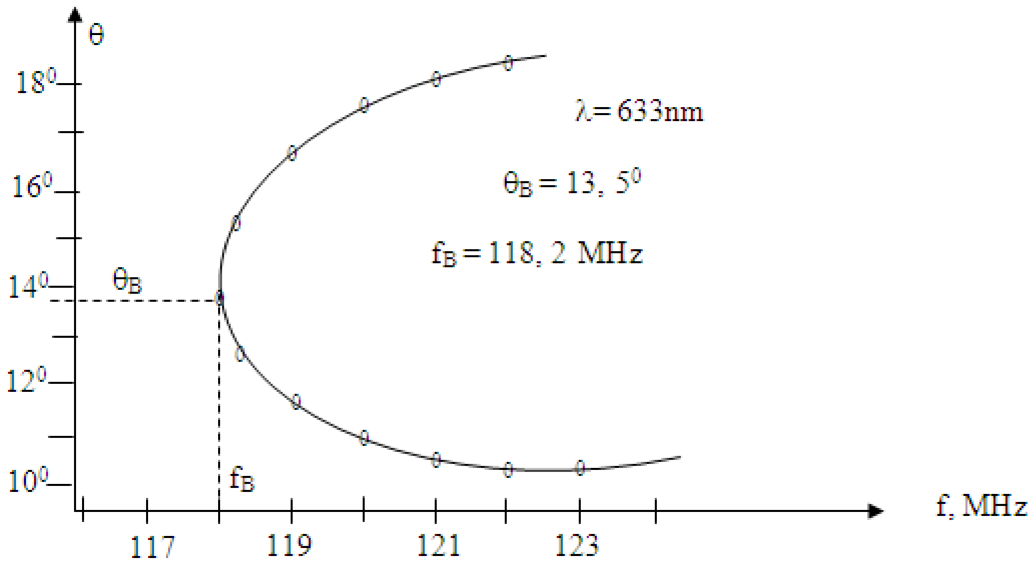

Fig. 11 Frequency dependence of the angle of incidence

The values of the indexes of refraction n_i= 2.26 and n_e = 2.41 and acoustic velocity V= 7.25 x 10^5m/s were used. Bragg angle θ_B corresponding to large angular geometry of interaction is equal to θ_B=13.5°.The curve $\theta(f)$ at frequency f=118.2MHz and $\theta = \theta_B$ has a vertical section. It means that the wave vector synchronism condition permits large variations of angle of incidence of light. Experimentally determined dependence $\theta(f)$ is in good agreement with the results of calculation.

Spectral bandwidth of the filter $\Delta\lambda$ measured at λ = 633nm with a collimated laser beam does not exceed the value $\Delta\lambda$= 13nm. The bandwidth was calculated using equation (9), and the frequency band Δf is shown in fig. 12.

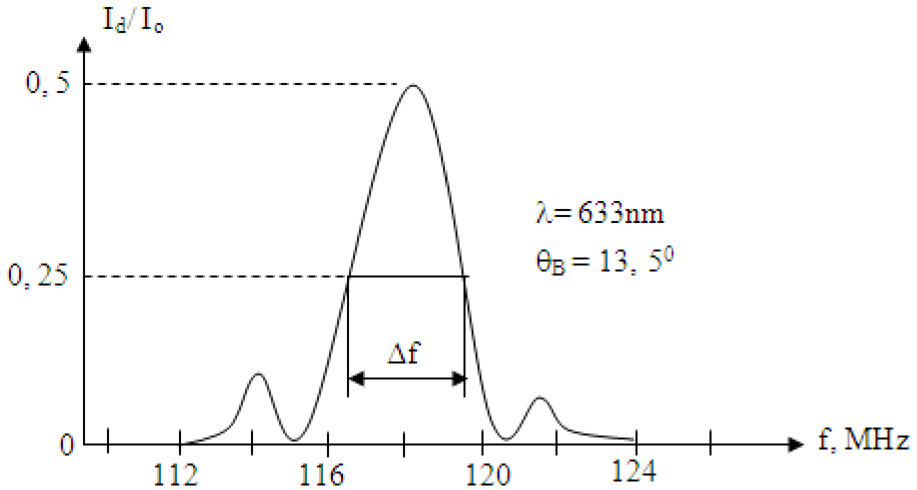

Fig. 12 Diffraction efficiency frequency dependence

The dependence I_d/I_o upon the acoustic frequency was measured at λ = 633nm and $\theta = \theta_B$ using electric power P= 1.0W. The spectral resolution is determined by angular divergency of an acoustic beam mainly.

CONCLUSION

It should be concluded that the operation of the device was examined in diffraction efficiency regime $I_d/I_o \leq 0.5$. It was found experimentally that the increase of drive electric power up to P= 2.0W produces the transmission growth T= 90%. However, the operation of the acousto-optic filter with diffraction efficiency is $I_d/I_o > 0.5$ is not desirable. Transmission dependence on electric drive power becomes non-linear. There is no guarantee that the increase of drive power will not be accompanied by acoustic non-linearity of the medium. As a result additional maximum may occur on the spectral transmission curve, and the reasons are multiple acoustic frequencies. Besides, the increase of transmission T > 50% makes the usage of the filter on multifrequency regime due to severe influence of combination frequencies impossible. The output parameters of the filter are distorted in this area.

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