Quantum Electronics **35** (11) 1057 – 1063 (2005)

PACS numbers: 42.79.Jq; 43.35.Sx
DOI: 10.1070/QE2005v035n11ABEH013035

Tunable acousto-optic filters with the multiple interaction of light and sound

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Abstract. **Optical multipass schemes of the interaction of light and sound, which are promising for filtration of optical beams based on tunable acousto-optic filters, are studied. The features of operation of acousto-optic filters in the rejection and transmission regimes are considered. It is proved theoretically and confirmed experimentally that the use of multiple interaction improves the spectral and energy parameters of acousto-optic devices. The collinear and transverse geometry of acousto-optic interaction in cells based on a paratellurite crystal is studied in the double-pass, three-pass, and multipass diffraction regimes.**

Keywords: *acousto-optics, tunable acousto-optic filter, spectral transmission band, diffraction efficiency, paratellurite crystal.*

1. Introduction

It is known that acousto-optic devices are widely used in science and technology to control the parameters of light [1, 2]. Acousto-optic interaction is employed for the development of compact, reliable, and fast devices for modulation, scanning, and filtration of optical radiation. The elaboration of acousto-optic filters with high spectral resolution attracts recent interest. This is caused by the rapid development of WDM fibreoptic communication systems [3 – 12]. Although tunable acousto-optic filters have a relatively low spectral resolution, they operate faster and more reliably and can be tuned in a broader spectral range than other filtration systems. In addition, acousto-optic devices can operate in multichannel and multifunctional regimes, which cannot be realised in alternative filtration systems.

At present filters based on a paratellurite crystal (TeO_2), in which nearly collinear geometry of acousto-optic interaction is used, have one of the highest spectral resolutions [3 – 10]. However, the spectral parameters of even collinear devices do not always satisfy practical requirements. Therefore, one of the important problems is the improvement of operating parameters of acousto-optic filters. It is proposed to use for this purpose the multiple propagation of light beams through an acoustic column (region where an ultrasonic wave is excited). In this paper, we consider four relatively simple modifications of acousto-optic multipass TeO_2 crystal filters. Two of them, namely, a double-pass rejection filter and a bandpass filter with multiple propagation of light through an ultrasonic column allow one to reduce the power of a control electric signal. Two other modifications including a double-pass and a three-pass filter provide a narrower spectral filtration band.

2. Single-pass rejection acousto-optic filter

It is known that an acousto-optic cell can be used to manufacture a rejection filter by using zero-order diffraction beams [11 – 13]. Such a device reduces the intensity of only those spectral components of the input optical signal that are located within the narrow spectral interval $\Delta\lambda$, whereas the rest of the components of this signal are transmitted by the device. In this case, both the spectral interval in which the signal is suppressed and the rejection factor are controlled by an electric voltage.

The main parameter characterising the operation of an acousto-optic cell is the diffraction efficiency ξ. It is determined by the ratio of the light intensity I_1 at the cell output to the input radiation intensity I [1, 2]

$$\xi = \frac{I_1}{I} = 1 - \frac{I_0}{I}, \tag{1}$$

where I_0 and I_1 are the light intensities at the filter output in the zero and first diffraction orders. It is known that the signal rejection factor is one of the main characteristics of a rejection filter [13]. This coefficient depends on the diffraction efficiency as

$$\chi = 10\lg(1 - \xi) = 10\lg\frac{I_0}{I}. \tag{2}$$

Another important characteristic of rejection filters is the spectral band $\Delta\lambda$ in which a signal is suppressed. This characteristic corresponds to the transmission band of a bandpass filter [1 – 14].

It is known that the light intensity in the zero diffraction order is determined by the expression [2]

$$\frac{I_0}{I} = 1 - \frac{q^2}{q^2+\eta^2}\sin^2\left[\left(q^2+\eta^2\right)^{1/2}\frac{l}{2}\right], \tag{3}$$

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Received 11 July 2005; revision received 26 September 2005
Kvantovaya Elektronika **35** (11) 1057 – 1063 (2005)
Translated by M.N. Sapozhnikov

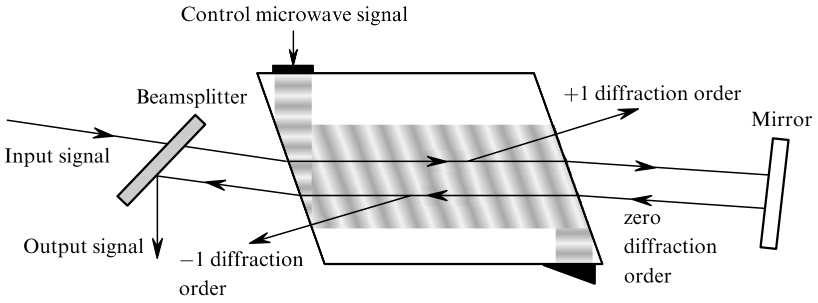

Figure 1. Scheme of a double-pass rejection filter.

where l is the length of interaction of light and sound; η is the phase-matching coefficient; q is the coupling coefficient depending on the acoustic wave power P_s as $q \sim P_s^{1/2}$. As a rule, the ultrasonic power is close to that of the electric control signal applied to the cell. The phase-matching coefficient shows how the Bragg condition is violated depending on the wavelength of light, the ultrasonic frequency or the angle of incidence of an optical beam on the acoustic wave front. The narrow spectral band $\Delta\lambda$ of the filter and the high signal rejection factor χ are obviously achieved for a large length l of interaction of light and sound because the product ηl increases with increasing the length, which affects the diffraction efficiency [1–6]. This means that the collinear or nearly collinear geometry of acousto-optic interaction is most convenient for manufacturing a rejection filter [3–10]. It is known that the maximum diffraction efficiency $\xi = 1$ in acousto-optic devices never can be achieved because ultrasonic and light beams are not plane waves. Therefore, the signal rejection factor in a rejection filter is always finite: $-\infty < \chi < 0$.

Filtration was experimentally studied by using a quasi-collinear filter based on a paratellurite crystal operating at a wavelength of 633 nm. The phase velocity of acoustic waves in the crystal was directed at an angle of $\alpha = 2°$ to the [110] axis, and the acousto-optic interaction length was $l = 2.5$ cm. For the electric power $P = 310$ mW, a rather high diffraction efficiency $\xi = 0.97$, corresponding to the rejection factor $\chi = -15$ dB, was achieved in the cell. Our measurements showed that the spectral band of the filter at a wavelength of 633 nm was $\Delta\lambda = 1.2 \pm 0.1$ Å. This means that the signal suppression band at a wavelength of 1550 nm, which is used in WDM communication links, achieves 7.2 Å.

3. Double-pass rejection filter

It is known that the requirements imposed on the signal rejection factor χ in most rejection filters used in modern fibreoptic communication links are very high [9–12]. For this reason, the signal rejection factor $\chi = -15$ dB of the filter under study is insufficient. However, this coefficient can be increased by using a double-pass optical filtration system.

A double-pass acousto-optic filter can be manufactured by several methods. A variant of the filter studied here is shown in Fig. 1. A specific feature of the filter is that radiation in the zero diffraction order is directed again to the filter toward the incident radiation. Light beams propagated through the cell in the forward and backward directions are separated by a beamsplitter and then a light beam, which passed twice through the cell, is incident on a detector. The calculation showed that the light intensity at the filter output in the double-pass regime is determined by the expression

$$\frac{I_0}{I} = \left\{1 - \frac{q^2}{q^2+\eta^2}\sin^2\left[\left(q^2+\eta^2\right)^{1/2}\frac{l}{2}\right]\right\}^2. \qquad (4)$$

It follows from expressions (3) and (4) that the signal suppression band $\Delta\lambda$ in the double-pass regime is broader than that for a similar single-pass filter. It also follows from (2) and (4) that the double-pass filtration scheme doubles the rejection factor in the general case. This means that the specified rejection factor in a double-pass filter can be achieved at a lower power of the control electric signal than in the case of a single-pass filter.

To verify the theoretical conclusions, we fabricated a double-pass rejection filter based on a singe-pass device. The experimental study of this filter showed that the double-pass filtration did result in the increase in the signal rejection factor. However, this factor was increased from −15 to −22 dB rather to −30 dB, as predicted by (4). The discrepancy between theoretical and experimental data is explained by the fact that both acoustic and light waves are not plane waves and have a certain divergence. Despite a finite divergence of light beams, good agreement between theoretical and experimental data was observed at a low power of the control signal ($P < 150$ mW). This is demonstrated in Fig. 2, where the dependences of the rejection factor χ on the control power P are shown for single-pass and double-pass filters. Curve (*1*) in Fig. 2 is plotted by fitting the experimental data by the method of least squares.

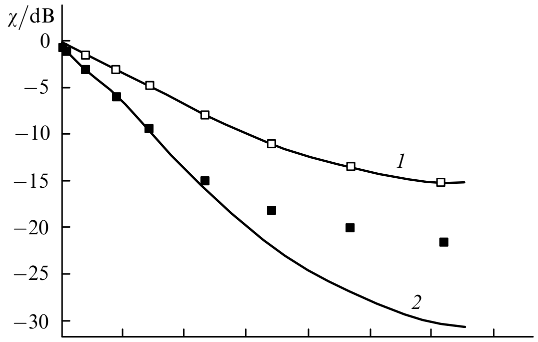

Figure 2. Signal rejection factor for single-pass (*1*, □) and double-pass (*2*, ■) filters. Curves are calculations, squares are experiment.

Curve (*2*) describing the signal rejection factor in the double-pass filter is constructed by using curve (*1*) and expressions (2) and (4).

Our experiments showed that the signal rejection spectral band in the double-pass filter was broader than that in the single-pass filter. Figure 3 presents the dependences of the signal rejection band $\Delta\lambda$ in the double-pass and single-pass filters on the control signal power P. One can see that the double-pass system does not improve the spectral resolution compared to the single-pass system (unlike the advantage in the rejection factor).

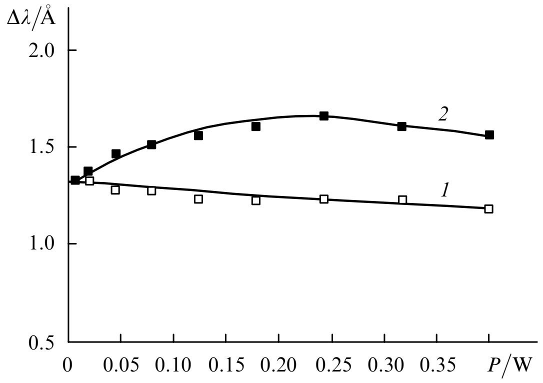

Figure 3. Signal spectral rejection bands for single-pass (*1*, □) and double-pass (*2*, ■) filters. Curves are calculations, squares are experiment.

Practically important characteristics of an acousto-optic device are the radiation divergence and the spatial structure of the output optical beam. It is obvious that the divergence of the light and acoustic beams and a complicated and inhomogeneous energy distribution in the acoustic column cross section lead, as a rule, to the wave-front distortions and spreading of the cross-section boundaries of output beams. Figure 4 presents the photographs of light intensity distributions at the output face of a paratellurite crystal in the single-pass and double-pass regimes. Each of the photographs shows the transverse dimensions of the TeO_2 crystal (1.0×1.5 cm). The crystal was illuminated by a broad collimated monochromatic light beam. It is obvious that dark spots at the centre of the output face of the crystal appeared due to diffraction of light from an acoustic wave. During acousto-optic interaction, radiation is partially removed from the incident light beam and is deflected in the direction of the first diffraction order. The higher the diffraction efficiency in the crystal, the lower the transmitted light intensity and the darker is a spot at the crystal centre. One can see from Fig. 4 that the spot structure in the zero diffraction order is quite inhomogeneous both upon single and double propagation of light through the cell. However, in the case of the double-pass filter, the spot size proves to be larger and the spot itself becomes darker than in the single-pass filter. This means that the signal rejection factor increases in the double-pass filter.

Our experiments also showed that the cross section and structure of the light beam in the zero diffraction order noticeably changed in the crystal compared to the cross section and structure of the incident beam. If the filter is used in fibreoptic communication links, these variations are undesirable from the practical point of view because they can increase losses upon coupling radiation into the fibre. However, a noticeable increase in the signal rejection factor in a rejection filter makes the use of double-pass acousto-optic filters expedient.

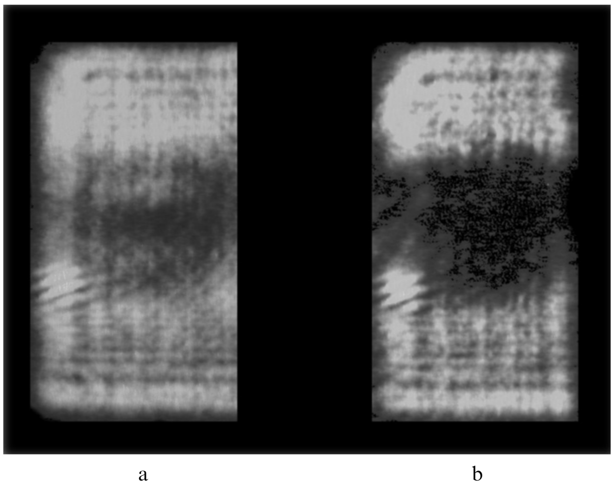

Figure 4. Output light intensity distributions for single-pass (a) and double-pass (b) rejection filters.

4. Multipass bandpass filter

Investigations performed in this paper showed that the double-pass filter provides the maximum diffraction efficiency at a lower power of the control electric signal. Therefore, it is reasonable to assume that this power can be reduced much greater than in the double-pass scheme if the optical beam propagated through the filter several times [2]. We can also expect that the best result will be achieved when an acoustic-optic cell is placed inside an optical resonator. This forms the basis of the operation of a multipass bandpass filter.

Obviously, it is most convenient to fabricate multipass bandpass filters by using ring resonators in which light propagates not in two directions, as in a usual filter, but only in one direction. The advantage of such a scheme is that the light diffracted after each interaction with sound propagates in the same direction.

It is known that there exists in a resonator a limited set of wavelengths of light corresponding to different resonator modes. The spectral width of an individual mode is determined by optical losses in the system. Because an acousto-optic cell introduces considerable losses into the resonator and the intermode spacing in the resonator is much smaller than the bandwidth $\Delta\lambda$ of the acousto-optic filter, resonance effects can be neglected.

By studying the multipass filtration system, we found that, if the acoustic wave power P_s provides the diffraction efficiency ξ per passage of light through a sound column, then the interaction efficiency in the multipass regime is

$$\xi_{\mathrm{m}} = \sum_{n=0}^{\infty}(1-\xi)^n(1-R)^n, \tag{5}$$

where n is the summation index equal to the number of passages of light through the sound column and R is the loss coefficient in the system. The light power losses are determined by optical losses at mirrors and reflections of

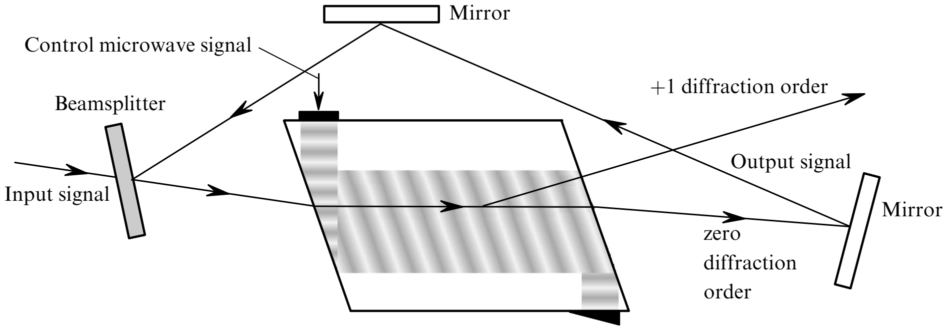

Figure 5. Scheme of a multipass rejection filter.

light from the input and output faces of the paratellurite crystal. As follows from (5), in the ideal case of the absence of losses, the diffraction efficiency proves to be maximum, i.e., $\xi_{\mathrm{m}} = 1$ for any nonzero values of the control power P. On the other hand, it is obvious that if the control power provides the diffraction efficiency for a passage close to unity, then the repeated passages of light through the cell result only in a small increase in the total diffraction efficiency ξ_{m} compared to ξ. Therefore, the multipass filtration system does not provide any advantage in the transmission coefficient of the device if the control power is high. As for the spectral transmission band, it follows directly from (4) and (5) that the transmission band of a multipass filter broadens when the diffraction efficiency is high.

One of the simplest schemes of a multipass filter with a three-mirror optical resonator is shown in Fig. 5. One of the resonator mirrors is used as a beamsplitter directing the input optical beam into the resonator. Unfortunately, the use of a partially transparent mirror gives rise to additional optical power losses in the system. However, this scheme is the most simple and convenient for studying multipass filters.

The dependence of the diffraction efficiency on the control signal power for a filter operating according to this scheme is shown in Fig. 6. One can see that the diffraction efficiency increases most noticeably at low powers P. For example, for $P \approx 20$ mW, the diffraction efficiency increased by a factor of three, being limited by the value 0.3. Therefore, if a crystal used in the filter is of a poor acousto-optic quality [1, 2] or the filter is used in the multichannel operation regime, the use of the multipass filtration scheme becomes justified despite a weak broadening of the transmission band of the filter (Fig. 7).

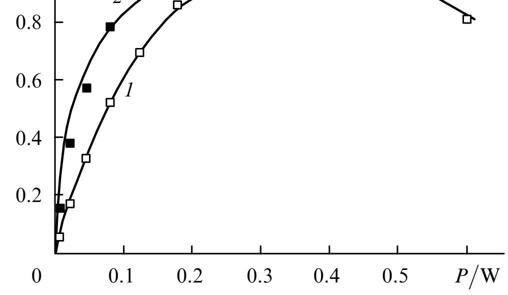

Figure 6. Light diffraction efficiency for single-pass (*1*, □) and multipass (*2*, ■) filters. Curves are calculations, squares are experiment.

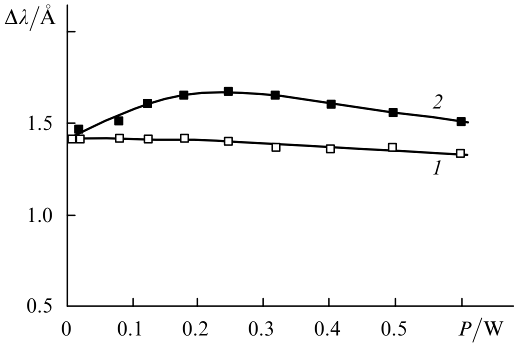

Figure 7. Signal transmission bands for single-pass (*1*, □) and double-pass (*2*, ■) filters. Curves are calculations, squares are experiment.

5. Double-pass bandpass filter

It is known that the main problem in the fibreoptic communication systems is not the increase in the diffraction efficiency but the achievement of a high spectral resolution and narrowing of the spectral transmission band $\Delta\lambda$ of the filter. It was found that there exist filtration schemes that can provide some narrowing of the transmission band of an acousto-optic device. One of the possible schemes of a double-pass filter is shown in Fig. 8.

It was shown experimentally that if light in the first diffraction order is directed backward into a cell, it diffracts again from an ultrasound wave if the Bragg phase-matching condition is fulfilled for optical beams propagating in the forward and backward directions. The light, which interacted twice with ultrasound, propagates toward the input light beam, whereas the optical beams entering the cell and leaving it are separated by a beamsplitter.

The light intensity I_2 at the filter output in the simplest case of the absence of optical losses in the system is determined by the expression

$$\frac{I_2}{I} = \frac{q^4}{\left(q^2+\eta^2\right)^2} \sin^4\left[\left(q^2+\eta^2\right)^{1/2} \frac{l}{2}\right]. \tag{6}$$

One can see from (6) that the use of the double-pass filtration system leads to the narrowing of the transmission band of the device. However, analysis of expression (6) shows that almost always, except the case $ql = \pi$, the

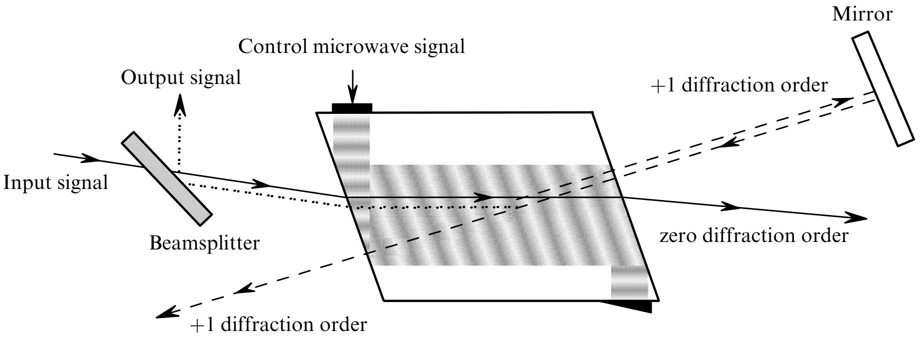

Figure 8. Scheme of a double-pass bandpass filter.

diffraction efficiency in the double-pass system is lower than that in the single-pass system.

To verify these assumptions, we fabricated a double-pass filter. We measured in experiments the dependences of the diffraction efficiency and the spectral transmission band $\Delta\lambda$ on the control signal power. These dependences are shown in Figs 9 and 10, respectively. One can see that the experimental results obtained for the double-pass filter are in good agreement with calculations. As expected, the transmission band of the double-pass filter decreased approximately by a factor of 1.4 and achieved 0.7 ± 0.06 Å at a wavelength of 633 nm. Such a spectral resolution corresponds to the transmission band $\Delta\lambda = 4.2$ Å when the device operates at a wavelength of 1550 nm. An additional advantage of the double-pass filtration scheme is the increase in the intensity of side maxima of the transfer function of the acousto-optic cell [14–17]. For example, we observed the threefold suppression of the intensity of side maxima of the instrumental function of the filter. Note that the double-pass system is simpler than the known filtration systems, for example, those in which two acousto-optic cells placed directly one after another are used [14–17].

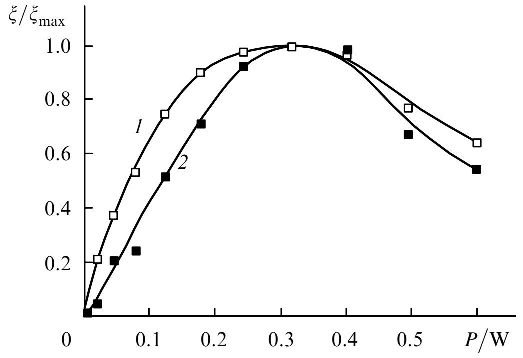

Figure 9. Light diffraction efficiency for single-pass (*1*, □) and double-pass (*2*, ■) filters. Curves are calculations, squares are experiment.

Note that almost all the results presented in this paper and obtained with the help of the quasi-collinear filter cell were verified in operation with the noncollinear device based on a TeO_2 crystal in which the transverse, i.e., wide-aperture geometry of the acousto-optic interaction was used [1–3]. The results of experiments with devices of two types well agree with each other and with theoretical conclusions.

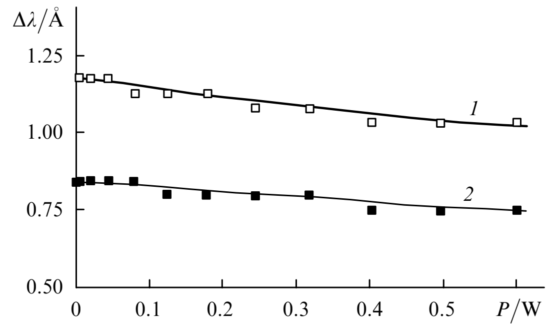

Figure 10. Signal transmission bands for single-pass (*1*, □) and double-pass (*2*, ■) filters. Curves are calculations, squares are experiment.

6. Three-pass bandpass filter

As shown in the previous section, the use of the double-pass filtration system results in the narrowing of the spectral transmission band by a factor of 1.4. However, it follows from calculations that there is no point in fabricating filters in which the diffracted light propagates through a cell many times. For example, sixfold passage of a light beam through a sound column reduces the transmission bandwidth of the device only by half. Note that the systems under study contain inevitably optical losses due to reflection of light from the crystal faces and the use of beamsplitters. For this reason, to obtain a stronger narrowing of the transmission band and to reduce optical losses, a scheme of the multipass interaction is required, which differs from the scheme using a simple increase in the number of passages of light through the sound column.

One of such filtration schemes studied here is shown in Fig. 11. In this scheme, light propagates through a crystal three times. A specific feature of the scheme is a certain choice of the propagation direction of light beams. One can see from Fig. 11 that the incident light first propagates in the cell at the Bragg angle corresponding to the wavelength λ_1, as in a usual filter. Because of this, the spectrum of light filtered after the first passage is located in the wavelength range from $\lambda_1 - \Delta\lambda/2$ to $\lambda_1 + \Delta\lambda/2$, where $\Delta\lambda$ is the spectral transmission band of the filter for single interaction. After the first interaction, the diffracted light beam is again directed to the crystal by a mirror. However, in this case the light propagates at a different angle to the acoustic wave front compared to the first interaction. The phase-matching condition during the second passage is fulfilled at the

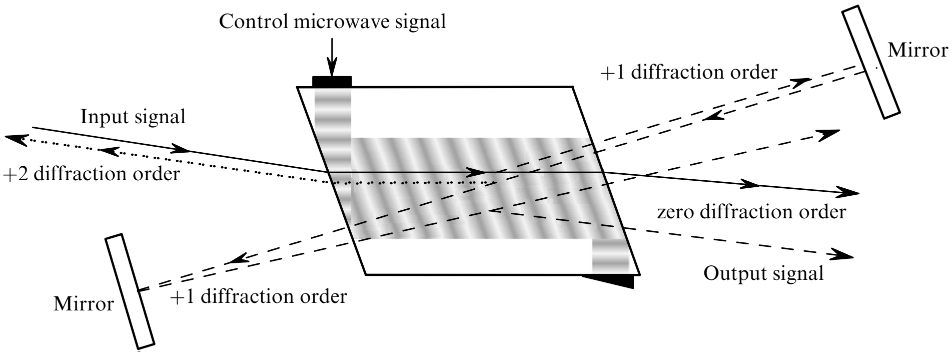

Figure 11. Scheme of a three-pass bandpass filter.

wavelength λ_2, which is also located within the interval $\lambda_1 \pm \Delta\lambda/2$. Analysis showed that the spectrum of light that did not diffract from the acoustic wave upon the second passage has two maxima bands, the width of each of them being $\sim \Delta\lambda/2$.

Obviously, the existence of two maxima in the transfer characteristic of a filter is unacceptable. To suppress one of them in the spectrum of radiation propagated twice through the cell, it is necessary to pass this radiation again through the ultrasonic column. During the third passage, the Bragg condition is fulfilled only for the light wavelength λ_3 corresponding to one of these maxima. It is obvious that the third passage of light thorough the sound column results in the additional narrowing of the transmission band of the device and also in the suppression of the side maxima of the transfer characteristic.

The output light intensity I_3 of such a filter is described by the expression

$$\frac{I_3}{I} = \xi(\lambda_1)\xi(\lambda_2)[1 - \xi(\lambda_3)], \tag{7}$$

where $\xi(\lambda_1)$, $\xi(\lambda_2)$, and $\xi(\lambda_3)$ are the diffraction efficiencies at the corresponding wavelengths. It follows from (7) that there exists the inevitable power losses of an optical signal filtered in the three-pass system. However, the absence of a beamsplitter in this filter is an advantage.

To verify the results of theoretical analysis, we measured the dependences of the diffraction efficiency on the electric signal power, which are presented in Fig. 12. One can see that the three-pass filter, as the two-pass filter, does not provide any advantage in the diffraction efficiency. Note that the maximum diffraction efficiency in the three-pass filter is achieved at somewhat higher acoustic power than in the two-pass filter. This feature follows directly from expression (7). Our measurements showed that the general form of the calculated dependence of the spectral transmission band on the ultrasonic power was in good agreement with the characteristic of the real device. It follows from Fig. 13 that the most narrow transmission band of the filter $\Delta\lambda = 0.6 \pm 0.05$ Å is achieved for the maximum diffraction efficiency, whereas the transmission band of this filter in the single-pass regime is $\Delta\lambda = 1.2 \pm 0.1$ Å.

Therefore, the three-pass filtration scheme provides the narrowing of the filtration band by half. This means that such a scheme is promising for using in acousto-optic filters. However, the three-pass filtration system requires very precise adjustment of the optical scheme of the device, the complexity of the adjustment increasing with improving the spectral resolution of the filter. For example, the experiment showed that the rotation of one of the mirrors in the three-pass system through an angle of $\sim 10'$ reduced the diffraction efficiency from its maximum value to almost zero. Nevertheless, this disadvantage is not decisive and the three-pass scheme can be recommended for using in acousto-optic systems for filtration of optical signals.

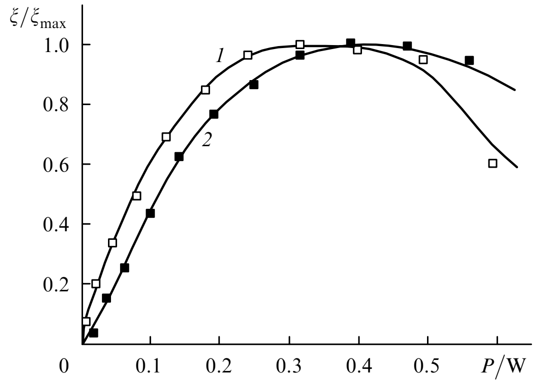

Figure 12. Light diffraction efficiency for single-pass (*1*, □) and three-pass (*2*, ■) filters. Curves are calculations, squares are experiment.

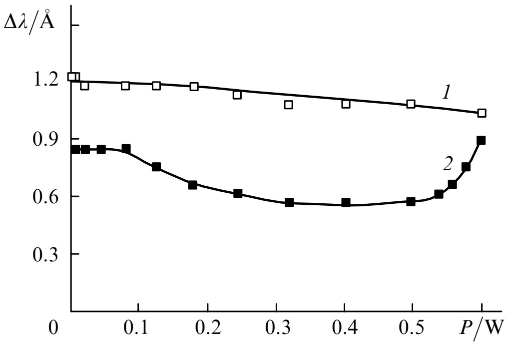

Figure 13. Signal transmission bands for single-pass (*1*, □) and three-pass (*2*, ■) filters. Curves are calculations, squares are experiment.

7. Conclusions

Our theoretical and experimental studies have shown the use of filtration schemes with multiple interaction of light and sound in rejection and bandpass acousto-optic devices is quite promising. The multipass filters investigated in the paper have better characteristics (spectral resolution, diffraction efficiency, and consumed electric power) than conventional single-pass acousto-optic devices.

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