Quantum Electronics **38** (1) 46 – 50 (2008)

ACOUSTO-OPTICS

PACS numbers: 42.79.Hp; 42.79.Ci
DOI: 10.1070/QE2008v038n01ABEH013681

Influence of nonreciprocal effect on the operation of a collinear acousto-optic filter

Yu.S. Dobrolenskiy, V.B. Voloshinov, Yu.A. Zyuryukin

***Abstract*. The nonreciprocal effect is studied theoretically and experimentally by the example of collinear acousto-optic interaction in a birefringent crystal. It is shown that this effect at ultrasonic frequencies ~1 GHz and above considerably influences the parameters of modern acousto-optic devices, in particular, tunable acousto-optic filters. The nonreciprocal effect is estimated for different acousto-optic materials.**

Keywords: *acousto-optic interaction, nonreciprocal effect, collinear acousto-optic filter, lithium niobate.*

1. Introduction

The interaction of electromagnetic and acoustic waves is widely used in modulators, deflectors, and filters to control the temporal and spatial parameters of optical radiation. Acousto-optic (AO) interaction can be also used in optoelectronic devices operating in optical communication and data processing systems [1 – 7]. In particular, AO filters are widely used in optics, quantum electronics, and laser techniques to separate one or several narrowband components from an optical signal with an intricate spectrum. It is known that one of the interaction regimes actively used in AO filters is collinear Bragg diffraction at which the wave and ray vectors of light and ultrasound are collinear. In this geometry, the largest interaction length of optical and acoustic waves can be realised, which corresponds to the diffraction grating with a large number of lines. It is known that the transmission band of a filter narrows down with increasing the number of grating lines and, therefore, the spectral resolution $R = \lambda/\Delta\lambda$ of the filter increases, where λ is the light wavelength and $\Delta\lambda$ is the transmission bandwidth [1 – 4]. At present the best collinear AO filters applied, for example, in fibreoptic communication lines have the spectral resolution of $10^3 - 10^4$ [5 – 8].

The development of acousto-optics involves the mastering of progressively higher frequencies, and now AO devices are fabricated in which a sound wave can be excited at frequencies up to a few gigahertz [9, 10]. At such high frequencies, effects become noticeable which have been neglected earlier. Among these effects is the AO interaction nonreciprocity, which consists in the difference of AO diffraction parameters during the propagation of light in opposite directions.

It is known that due to the Doppler effect during AO interaction, the frequency of diffracted light shifts with respect to that of the incident light wave [1 – 4]. If the propagation direction of light is changed to the opposite, the propagation direction of ultrasound remaining the same, this shift changes its sign. It follows from vector diagrams [1 – 4] that the ultrasonic frequency F corresponding to the Bragg matching condition also proves to be different for these two cases, the frequency shift δF taking place for any AO interaction geometry, its value being proportional to the acoustic wave frequency. The calculation shows that at frequencies $F \approx 1$ GHz and radiation wavelengths in the visible spectral region, the relative change in the acoustic frequency of the Bragg synchronism is $\delta F/F \sim 10^{-4}$. On the other hand, the reciprocal spectral resolution $1/R = \Delta\lambda/\lambda$ of AO filters is of the same order of magnitude. Because $\Delta\lambda/\lambda = \Delta F/F$ in AO cells [1], where ΔF is the acoustic frequency bandwidth, the Doppler frequency shift proves to be comparable with the transmission bandwidth of the AO filter. This indicates that the nonreciprocal effect should be taken into account in the design of high-frequency AO devices, for example, high-resolution filters.

Although the nonreciprocal effect in the AO interaction was investigated in a number of papers [11 – 17], its role remains inadequately studied, especially in the case of the anisotropic diffraction of light. This paper is devoted to the theoretical and experimental study of the nonreciprocal effect by the example of collinear diffraction. This geometry was chosen because in this case the transmission bandwidth of the device is smallest and, hence, the nonreciprocal effect is strongest. It is known that the collinear interaction regime can be obtained in crystals of lithium niobate, quartz, calcium molybdate, tellurium, and Tl_3AsSe_3 (TAS) [1]. We studied experimentally a $LiNbO_3$ crystal for $\lambda = 632.8$ nm and $F = 883$ MHz.

2. Nonreciprocal effect upon AO interaction

It is known that in the absence of the phase mismatch the wave vectors of the incident light ($\boldsymbol{k}_i$), diffracted light ($\boldsymbol{k}_d$), and ultrasound ($\boldsymbol{K}$) form a closed set of three vectors. Upon diffraction to the +1st order, the condition $\boldsymbol{k}_d =$

Yu.S. Dobrolenskiy, V.B. Voloshinov Department of Physics, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119991 Moscow, Russia; e-mail: dobrolenskiy@phys.msu.ru, volosh@phys.msu.ru;
Yu.A. Zyuryukin Saratov State Technical University, ul. Politekhnicheskaya 77, 410054 Saratov, Russia; e-mail: phys@sstu.ru

Received 5 July 2007; revision received 28 September 2007
Kvantovaya Elektronika **38** (1) 46 – 50 (2008)
Translated by M.N. Sapozhnikov

$\boldsymbol{k}_i + \boldsymbol{K}$ is fulfilled, and upon diffraction to the −1st order – the condition $\boldsymbol{k}_d = \boldsymbol{k}_i - \boldsymbol{K}$. The vector diagrams are usually constructed so that the vectors $\boldsymbol{k}_i$ and $\boldsymbol{k}_d$ end on the same wave surface (in the case of isotropic diffraction) i.e. they have the same length. In reality, as mentioned in Introduction, the frequencies of incident and diffracted light slightly differ from each other. Therefore, the lengths of their wave vectors $\boldsymbol{k}_{i,d}$ are also slightly different because the wave number k and the refractive index n are related by the expression $k = (\omega/c)n$, where ω is the circular frequency, c is the velocity of light in vacuum, and the direction of the vector $\boldsymbol{k}$ coincides with that of the wave normal. In particular, upon diffraction to the +1st order, $\omega_d > \omega_i$ (where ω_i and ω_d are the frequencies of incident and diffracted light, respectively) and $|\boldsymbol{k}_d| > |\boldsymbol{k}_i|$. Upon diffraction to the −1st order, we have $\omega_d < \omega_i$ and $|\boldsymbol{k}_d| < |\boldsymbol{k}_i|$. It follows from this that in these cases the wave vector $\boldsymbol{K}$ and the acoustic frequency of the Bragg synchronism are also different.

The nonreciprocal effect upon isotropic AO interaction was studied in [13], where the expression

$$\delta F = \frac{4n^2V^2}{\lambda c} \tag{1}$$

was obtained for the Doppler frequency shift of ultrasound in the case of phase matching (V is the sound speed in a crystal). It follows from (1) that the nonreciprocal effect is stronger in material with a high sound speed and a large refractive index. In addition, because the frequency F is proportional to the ratio V/λ, we have $\delta F \sim F$, i.e. the frequency shift is proportional to the frequency itself.

Consider now the case of collinear AO diffraction. It is known that in practice only anisotropic (low-frequency) collinear geometry is used [1]. The vector diagram in this case, corresponding to diffraction to the +1st order, is shown in Fig. 1 by solid curves. It follows from considerations similar to those presented above that, taking into account the corrections described above, the diagram should be modified and vectors $\boldsymbol{k}_d$ and $\boldsymbol{K}$ should be replaced by vectors $\boldsymbol{k}_d'$ и $\boldsymbol{K}'$ shown by dashed curves in Fig. 1. Taking this into account, the moduli of the wave vectors of the interacting waves (hereafter, primes are omitted) are determined by the expressions

$$k_i = \frac{\omega_i}{c}n_i, \quad k_d = \frac{\omega_d}{c}n_d, \quad K = \frac{\Omega}{V}. \tag{2}$$

Here, n_i and n_d are the refractive indices at frequencies ω_i and ω_d, which are different due to the anisotropic nature of diffraction, and Ω is the ultrasonic frequency. Due to the Doppler effect, $\omega_d = \omega_i + \Omega$, and therefore, we can write

$$k_d = \frac{\omega_i + \Omega}{c}n_d. \tag{3}$$

The nonreciprocal effect introduces the correction not only to the diffracted light frequency ω_d but also to the refractive index n_d (due to dispersion). Let us denote the addition to the refractive index as

$$\delta n_d = n_d - n_{d0}, \tag{4}$$

where n_{d0} is the refractive index n_d at the frequency ω_i. Then, the change in the wave number of diffracted light can be written in the form

$$\delta k_d = \frac{\omega_i + \Omega}{c}(n_{d0} + \delta n_d) - \frac{\omega_i}{c}n_{d0}. \tag{5}$$

By removing the parentheses in (5), we obtain

$$\delta k_d = \frac{\Omega n_d + \omega_i \delta n_d}{c}. \tag{6}$$

On the other hand, it follows from expression (2) that the change in the length of the wave vector of ultrasound is $\delta K = \delta\Omega/V$. Because $\delta k_d = \delta K$ (phase matching condition), the change $\delta\Omega$ in the ultrasonic frequency is described by the expression

$$\delta\Omega = \frac{(\Omega n_d + \omega_i \delta n_d)V}{c}, \tag{7}$$

or

$$\delta F = \frac{(Fn_d + f_i \delta n_d)V}{c}, \tag{8}$$

where f_i is the incident light frequency.

It is known that the frequency F in the collinear interaction geometry is determined by the expression [1]

$$F = \frac{\Delta n V}{\lambda_i}, \tag{9}$$

where $\Delta n = |n_o - n_e| = |n_d - n_i|$ is the birefringence of a material; n_o and n_e are the ordinary and extraordinary refractive indices, respectively; and λ_i is the incident light wavelength. By substituting (9) into (8) and taking into account that $c = \lambda_i f_i$, we obtain

$$\delta F = \frac{\Delta n n_d V^2}{\lambda_i c} + \frac{\delta n_d V}{\lambda_i}. \tag{10}$$

At the same time, the change δn_d in the refractive index can be written in the form

$$\delta n_d = \frac{dn_d}{d\lambda}\delta\lambda. \tag{11}$$

Here, $dn_d/d\lambda$ characterises the dispersion of the refractive index and $\delta\lambda$ is the wavelength difference of diffracted and incident light. It is obvious that $\delta\lambda/\lambda_i = -\delta\omega/\omega_i = -\Omega/\omega_i$, and therefore, the relation

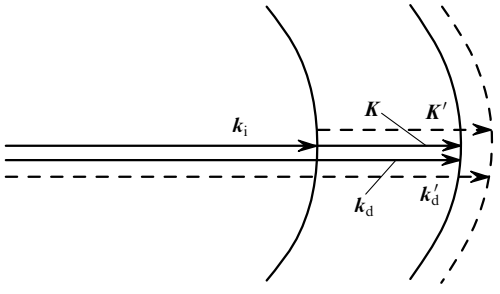

Figure 1. Vector diagram of collinear AO interaction.

$$\delta\lambda = -\lambda_i \frac{\Omega}{\omega_i} = -\lambda_i \frac{F}{f_i} \tag{12}$$

is valid, which, taking (9) into account, can be written in the form

$$\delta\lambda = -\frac{\lambda_i \Delta n V}{c}. \tag{13}$$

By substituting (13) into (11) and the obtained result to (10), we have

$$\delta F = \frac{n_d \Delta n V^2}{\lambda_i c}\left(1 - \frac{\lambda_i}{n_d}\frac{dn_d}{d\lambda}\right). \tag{14}$$

One can easily see that in the case of normal dispersion ($dn/d\lambda < 0$), the nonreciprocal effect is amplified. However, calculations show that the second term in (14) for most of the AO materials is approximately an order of magnitude smaller than the first term.

As pointed out above, when the incident light propagated in the opposite direction, diffraction occurs to the order with the opposite sign (the -1st order in the given case). It is obvious that in this case the acoustic frequency shift will have the same value but the opposite sign (the nonlinearity of the function $dn/d\lambda$ at a small wavelength interval can be neglected). Thus, the difference of ultrasonic frequencies corresponding to a strict phase matching condition during the propagation of light in opposite directions is equal to doubled expression (14)

$$\delta F = \frac{2 n_d \Delta n V^2}{\lambda_i c}\left(1 - \frac{\lambda_i}{n_d}\frac{dn_d}{d\lambda}\right). \tag{15}$$

The analysis of vector diagrams shows that, although the frequency of light diffracted to the $+1$st order is always higher than that of light diffracted to the -1st order, the mutual arrangement of the wave vectors $\boldsymbol{k}_i$, $\boldsymbol{k}_d$, and $\boldsymbol{K}$ can be chosen so that the acoustic diffraction frequency will be lower in the first case than in the second one. However, in this situation the ultrasonic frequency shift also has opposite signs for incident light propagating in opposite directions and relation (15) remains valid. Moreover, when the propagation direction of light is changed to the opposite and the optical mode of incident radiation is simultaneously changed, diffraction will occur to the same order, but the nonreciprocal effect will take place in this case as well. If the diffraction order is changed only by changing the optical mode, the addition to the ultrasonic frequency will have the same sign and the nonreciprocal effect will be absent. Thus, the necessary and sufficient condition for the manifestation of the nonreciprocal effect is the change in the propagation direction of light rather than the change in the diffraction order.

Note that the AO interaction exists not at a certain frequency but within some frequency band. Upon collinear diffraction, the width of this band (the transmission band of a collinear AO filter), defined as the full width at half-maximum (FWHM) of the diffraction efficiency, is described by the expression [1]

$$\Delta F = \frac{0.8\lambda_i F}{\Delta n L} = \frac{0.8 V}{L}, \tag{16}$$

where L is the interaction length.

It is obvious that for $\delta F \ll \Delta F$, the nonreciprocal effect does not influence significantly the operation of an AO filter. If, however, $\delta F \sim \Delta F$ or $\delta F > \Delta F$, the acoustic frequency shift caused by the nonreciprocal effect proves to be comparable with the filter transmission bandwidth or even exceeds it. Therefore, in practice the ratio $\delta F/\Delta F$ is important rather than the value of δF. According to (15) and (16), this ratio is

$$\frac{\delta F}{\Delta F} = \frac{2.5 n_d \Delta n V L}{\lambda_i c}\left(1 - \frac{\lambda_i}{n_d}\frac{dn_d}{d\lambda}\right). \tag{17}$$

Table 1 presents the values of $\delta F/\Delta F$ calculated for some widespread AO materials. The interaction length L corresponds approximately to real AO devices (for example, $L = 7.5$ and 4 cm for quartz and lithium niobate, respectively).

Table 1. Calculated values of $\delta F/\Delta F$ for collinear AO diffraction in various materials.

Crystal	Direction	Acoustic mode	λ/μm	V/km s^{-1}	F/MHz	$\delta F/\Delta F$ (%)
SiO_2	[100]	L	0.63	5.72	80	8
$CaMoO_4$	[100]	S	0.63	2.95	50	4
Tl_3AsSe_3	[100]	L	10.6	2.05	10	2
$LiNbO_3$	[100]	L	0.63	6.60	890	70
Te	[100]	L	10.6	2.45	320	17
TeO_2	[110]	S	0.63	0.616	150	8

Note: L is the longitudinal acoustic mode; S is the transverse acoustic mode.

Note that all AO crystals have directions along which the collinear interaction geometry is impossible due to the absence of the photoelastic effect (the so-called forbidden directions). For example, one of these directions is the [110] direction in a TeO_2 crystal presented in Table 1. However, it was shown in papers [18, 19] that such interaction geometry also can be used in practice for diverging light beams.

The data presented in Table 1 confirm that the influence of the nonreciprocal effect begins when acoustic frequencies approach the gigahertz range. According to Table 1, the maximum value of $\delta F/\Delta F$ is achieved in lithium niobate. Because of this, we studied experimentally the nonreciprocal effect in this crystal.

3. Experimental study of the nonreciprocal effect

We studied the nonreciprocal effect in an AO lithium niobate crystal cell, designed and fabricated at the Saratov State Technical University under supervision of one of the authors of this paper (Yu.A. Zyuryukin). Figure 2 shows the scheme of the cell.

A zinc oxide film piezoelectric transducer (PZT) is mounted on the cell end-face cut at 5° to the YZ plane of the crystal. A longitudinal acoustic wave excited by the transducer propagated through the crystal and having reflected from its opposite face, propagated in the opposite direction at a small angle to the incident wave. The propagation direction of the reflected wave coincided with the X axis of the crystal. A light wave propagated in the same (or opposite) direction. The possible orientations of its wave vector are shown by the heavy arrows in Fig. 2. Thus, we realised in the cell the collinear geometry of AO interaction on a longitudinal acoustic mode in the [100] direction with the interaction length of about 4 cm.

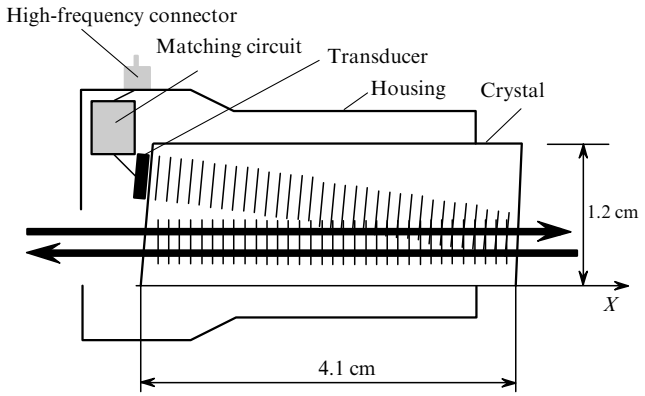

Figure 2. Scheme of a lithium niobate crystal AO cell.

By studying the parameters of the cell by the method of laser probing of a sound column, we determined the velocity $V = 6.6 \pm 0.1$ km s^{-1} of the ultrasonic wave and its decay coefficient $\beta = 0.9 \pm 0.1$ dB cm^{-1} at the frequency $F =$ 900 MHz. These values are consistent with the data [20] obtained for a longitudinal acoustic mode propagating in the [100] direction. The diffraction efficiency I_d/I_i (where I_d and I_i are the intensities of the diffracted and incident light, respectively) for the electric signal power $P \approx 500$ mW supplied to the PZT was $\sim 7\,\%$ in the collinear regime and $\sim 1.5\,\%$ in the orthogonal regime, which is typical for this material.

The effective length of the ultrasonic column estimated from the decay coefficient was 3.4 cm. Thus, due to the decay of ultrasound, the effective collinear interaction length obtained in experiments was $L_{eff} = 3.4$ cm, which increased the transmission bandwidth of the filter. In addition, it is known [1] that in the case of low diffraction efficiency, the transmission bandwidth of the filter increases by $\sim 12\,\%$ compared to the bandwidth determined by expression (16). Finally, the divergence of acoustic and light waves and their spatial inhomogeneity also cause the broadening of the transmission band. By neglecting the role of the latter factor, the calculated transmission bandwidth ΔF of the cell used in experiments was 175 kHz. Because the nonreciprocal ultrasonic frequency shift for lithium niobate calculated from (15) is about 100 kHz, the ratio $\delta F/\Delta F$ for this cell is $\sim 60\,\%$.

Figure 3 shows the scheme of the experimental setup for studying the nonreciprocal effect. A radiation source was 632.8-nm He–Ne laser (*1*). The laser beam reflected from mirrors (*2*) and (*3*) was incident on polariser (*4*) producing the required polarisation. The beam passed through aperture (*5*) and was incident on AO cell (*6*). To reduce crystal heating, ultrasound was excited in it in a pulsed regime by using a system consisting of pulse generator (*7*) and high-frequency generator (*8*). A signal was fed to the PZT from power amplifier (*9*). The diffracted wave propagated in the same direction as the incident wave; however, due to the anisotropic nature of diffraction, the polarisation planes of the incident and diffracted waves were mutually orthogonal. Radiation transmitted through the cell propagated then through apertures (*10*) and (*11*), which provided the propagation of light in the opposite direction strictly along the same path as in the forward direction. The separated diffracted wave behind analyser (*12*) was detected with photomultiplier (*13*), from which the signal was fed to oscilloscope (*14*) and was observed visually.

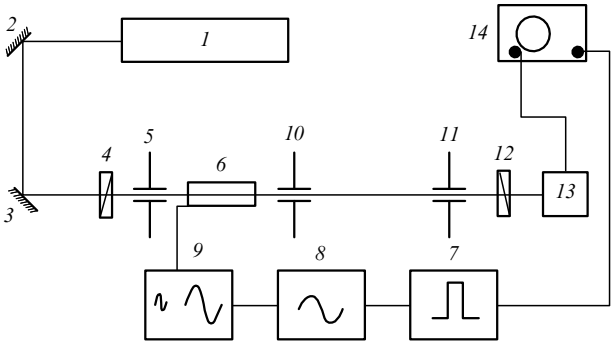

Figure 3. Scheme of the experimental setup: (*1*) He–Ne laser; (*2*, *3*) mirrors; (*4*) polariser; (*5*, *10*, *11*) apertures; (*6*) AO cell; (*7*) pulse generator; (*8*) high-frequency generator; (*9*) power amplifier; (*12*) analyser; (*13*) photomultiplier; (*14*) oscilloscope.

It is obvious that the width of the interaction band in the collinear geometry is minimal. Therefore, after the adjustment of the system to the maximum diffraction efficiency, the ultrasonic wave frequency was detected and the width of the interaction band was measured. Then, the laser and photodetector were interchanged and the experiment was repeated. By comparing the data obtained, we determined the magnitude of the nonreciprocal effect.

Our experiments showed that the acoustic wave frequency F corresponding to the maximum diffraction efficiency was ~ 883 MHz for the transmission bandwidth $\Delta F \approx 210 \pm 10$ kHz ($\Delta\lambda \approx 1.5$ Å). This gives the spectral resolution of the filter $R = F/\Delta F = \lambda/\Delta\lambda \approx 4200$.

The polarisation of the light wave was chosen so that the incident wave was an extraordinary wave and the diffracted wave – an ordinary wave. Because $n_e < n_o$ for lithium niobate (negative crystal), radiation propagating in the setup in Fig. 3 diffracted to the -1st order. The radiation propagating in the opposite direction diffracted to the $+1$st order. According to the vector diagrams, the frequency F in the first case should be lower than in the second case. The calculation of δF by expression (15) gives the value ~ 103 kHz, the contribution caused by dispersion being only 8 kHz.

The experiment confirmed the existence of the nonreciprocal effect. Figure 4 presents the dependences of the normalised intensity of diffracted light on the acoustic

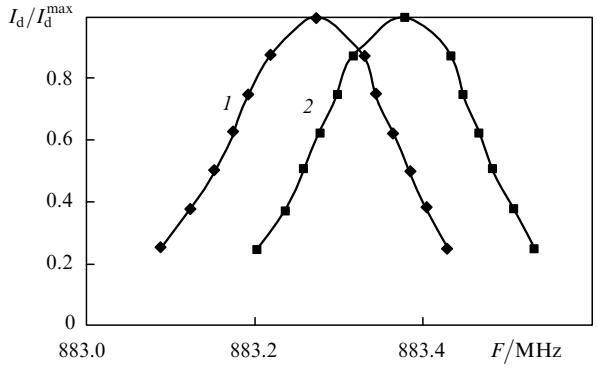

Figure 4. Dependences of the normalised intensity of diffracted light on the acoustic wave frequency F for counterpropagating light beams upon diffraction to the -1st (*1*) and $+1$st (*2*) orders.

frequency F. Curves (*1*) and (*2*) correspond to diffraction to the -1st and $+1$st orders, respectively. As follows from the analysis presented above, the maximum of curve (*2*) is located at a higher frequency than that of curve (*1*). The frequency shift due to the nonreciprocal effect was 104 ± 10 kHz, coinciding with the calculated value. Thus, the ratio $\delta F/\Delta F$ was ~ 50 %. It is obvious that this effect will be even more pronounced in the shorter-wavelength region.

Note that the ultrasonic frequency corresponding to the Bragg synchronism condition and, therefore, to the maximum effective diffraction proved to be strongly dependent on the crystal temperature. The corresponding experimental dependence is presented in Fig. 5 (measurements were performed for the -1st diffraction order). One can see that this dependence is linear and the heating of the crystal by 1°C leads to the decrease in the ultrasonic frequency by ~ 500 kHz. Therefore, to reduce the experimental error, ultrasound was excited in a pulsed regime with a large off-duty ratio.

Because, according to Fig. 5, the relative change in the resonance ultrasonic frequency due to crystal heating is ~ 0.1 %, the product ΔnV changes by the same magnitude. It is known [20] that the relative change in birefringence for lithium niobate in this case is $\sim 10^{-3}$%. Therefore, the resonance frequency decreases mainly due to a decrease in the sound speed V, whose relative change should be ~ 0.1 %. According to (15), the frequency shift due to the nonreciprocal effect is determined by the product $n_d \Delta n V^2$. The estimate shows that this product also changes approximately by 0.1 % in this temperature interval, which is two orders of magnitude smaller than the experimental error. Therefore, the nonreciprocal effect can be considered independent of temperature within the experimental error.

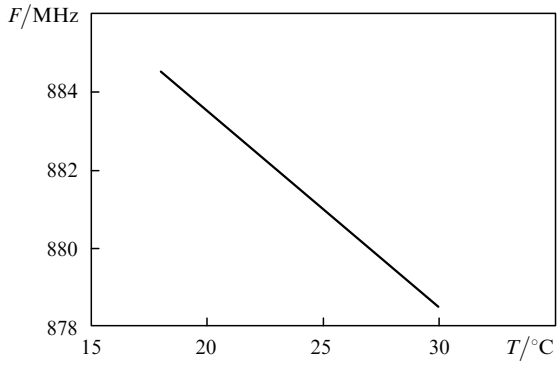

Figure 5. Temperature dependence of the ultrasonic frequency corresponding to the phase-matching condition.

4. Conclusions

We have studied the nonreciprocal properties of AO interaction in the collinear diffraction regime. It has been shown that the nonreciprocal frequency shift becomes comparable to the transmission bandwidth of a collinear AO filter when the frequency of acoustic wave approaches the gigahertz range. We have found experimentally that, when the light wave propagates in the opposite direction, the shift of the transmission band of the lithium niobate crystal AO cell achieves ~ 50 % of the bandwidth.

The results obtained in the paper prove the necessity of taking into account the nonreciprocal effect in the design of high-resolution AO devices operating with ultrasonic waves of super high frequency. Corrections to the resonance ultrasonic frequency caused by the Doppler effect are quite substantial and they should be taken into account especially in the cases when the multiple propagation of a light wave through an acoustic column is used in an AO filter [8] or successive diffraction to the $+1$st and -1st orders is realised [6, 7]. The nonreciprocal effect should inevitably affect the operation of intracavity AO devices [14–17]. However, it is also possible to develop elements of another type, for example, unidirectional couplers operating directly based on the nonreciprocal effect.

References

1. Balakshii V.I., Parygin V.N., Chirkov L.E. *Fizicheskie osnovy akustooptiki* (Physical Foundations of Acousto-Optics) (Moscow: Radio i Svyaz', 1985).
2. Korpel A. *Acousto-Optics* (New York: Marcel Dekker, 1988; Moscow: Mir, 1993).
3. Xu J., Stroud R. *Acousto-Optic Devices* (New York: Wiley, 1992).
4. Goutzoulis A., Pape D. *Design and Fabrication of Acousto-Optic Devices* (New York: Marcel Dekker, 1994).
5. Sapriel J., Charissoux D., Voloshinov V.B., et. al. *J. Lightwave Technol.*, **20**, 864 (2002).
6. Pozhar V.E., Pustovoit V.I. *Kvantovaya Elektron.*, **12**, 2180 (1985) [*Sov. J. Quantum Electron.*, **15**, 1438 (1985)].
7. Mazur M.M., Pozhar V.E., Pustovoit V.I., Shorin V.N. *Usp. Sovr. Radioelectron.*, **10**, 19 (2006).
8. Voloshinov V.B., Magdich L.N., Knyazev G.A. *Kvantovaya Elektron.*, **35**, 1057 (2005) [*Quantum Electron.*, **35**, 1057 (2005)].
9. Zyuryukin Yu.A., Ushakov N.M. *Izv. Vyssh. Uchebn. Zaved., Ser. Radiofiz.*, **27**, 1065 (1984).
10. Ushakov N.M., Zyuryukin Yu.A., Nikishin E.L. *Izv. Vyssh. Uchebn. Zaved., Ser. Radiofiz.*, **29**, 124 (1986).
11. Zil'berman G.E., Kupchenko L.F. *Radiotekh Electron.*, **20**, 2347 (1975).
12. Zil'berman G.E., Kupchenko L.F. *Radiotekh Electron.*, **24**, 901 (1979).
13. Golokoz P.P., Oboznenko Yu.L. *Radiotekh Electron.*, **32**, 15 (1987).
14. Golokoz P.P., Oboznenko Yu.L., Pugach I.P. *Kvantovaya Elektron.*, **13**, 164 (1986) [*Sov. J. Quantum Electron.*, **16**, 103 (1986)].
15. Zinov'eva T.V., Igmetov A.B., Kravtsov N.V., et al. *Kvantovaya Elektron.*, **19**, 142 (1992) [*Quantum Electron.*, **22**, 125 (1992)].
16. Kornienko L.S., Nanii N.V., Nanii O.E. *Kvantovaya Elektron.*, **17**, 1472 (1990) [*Sov. J. Quantum Electron.*, **20**, 1380 (1990)].
17. Nanii O.E. *Kvantovaya Elektron.*, **23**, 172 (1996) [*Quantum Electron.*, **26**, 168 (1996)].
18. Dobrolenskiy Yu.S., Voloshinov V.B., Parygin V.N. *Opt. Spektrosk.*, **98**, 673 (2005).
19. Dobrolenskiy Yu.S., Voloshinov V.B., Parygin V.N. *Proc. SPIE Int. Soc. Opt. Eng.*, **5828**, 16 (2005).
20. Shaskol'skaya M.P. (Ed.) *Akusticheskie kristally* (Acoustic Crystals) (Moscow: Nauka, 1982).