Acousto-optic modulators/frequency shifters with single-mode optic fibers

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Abstract. Acousto-optic modulators/frequency shifters based on TeO₂ crystals with single-mode optical fibers supporting and not supporting polarization for collimated and focused light beams at radiation wavelengths of 785, 1064, 1550 nm have been developed, produced and experimentally investigated. The mechanisms of formation and methods of expanding the working band of the modulator are determined. A double-crystal acousto-optic laser emission frequency shifter with an working bandwidth of ≈40 MHz has been created. Single-crystal modulators based on collimated beams with a frequency band of ≈10 MHz are considered. A single-crystal modulator with a focused light beam with a switching time of ≈ 18 ns and an extended reception band of ≈ 40 MHz is investigated. It is shown that a light beam focusing makes it possible to implement a modulator with a minimum switching time of ≈ (2-3) ns. This value is limited by electrical breakdown of the ultrasonic wave transmitter.

1. Introduction

The relevance of the development of acousto-optic (AO) devices built-in in fiber-optic lines (FOL) is due to the advantages of closed optical paths: a high degree of physical and information protection from external influences, reliability and stability of parameters in the absence of mechanical displacements, high speed, adaptable packaging of optical units in complex circuits and small dimensions, the possibility of switching optical signals in fiber communication lines [1]. In particular, modulators/frequency shifters with fiber outputs will be in demand when creating small-sized transportable optical and microwave frequency standards [2-4]. Acousto-optic modulators/frequency shifters with single-mode fiber outputs will be further referred to as the fiber AOMF for brevity.

The creation of fiber AOMF with low optical losses includes careful matching of FOLs, micro-lenses, and an acousto-optic cell (AOC), as well as their precision installation, alignment, and fixation. These operations require special equipment and additional labor costs that increases the cost of the devices. Moreover, their design fundamentally limits some important technical characteristics.

The purpose of this work is to develop and create modulators/frequency shifters with single-mode fiber outputs and to experimentally investigate their parameters; to study the mechanisms of formation and methods of expanding the working frequency band; to determine the effects limiting the minimum switching time of the AOMF and estimation of its value.
2. AOMF frequency band. Overall ratios

Let’s consider AOMF for the case of using a single-crystal paratellurite (TeO$_2$) as the acousto-optic cell (AOC) material, which has a unique combination of acoustic, optical, and acousto-optic properties [5] and allows efficient diffraction of both isotropic and anisotropic types.

Figure 1(1) shows a diagram of a single-crystal AOMF, where straight lines indicate the optical axes of the light beams. Since identical optical fibers (OF) are applied on both sides of the AOMF, the optical loss when the diffracted beam is introduced into the OF will be minimal in two cases:

1. a collimated light beam is used (the Rayleigh length of a Gaussian beam is much larger than the distance of the beam between collimators C1 and C2 [6]). They are used for stationary frequency shifters; they do not impose requirements on the AOMF speed;

2. converging light beam is focused in the center of the sound column (Rayleigh length is on the order of the length of the sound column). Focusers are installed instead of collimators. In this case, the requirements for the alignment of the AOMF elements are more stringent, since optical losses are critical to the distance from the focusators to the AOC, at the same time there is a possibility of rapid modulation of the beam intensity.

![Figure 1. Scheme of the developed fiber AO modulators: (1) single-crystal AOMF with a collimated or focused light beam; (2) double-crystal AOMF with a collimated light beam. C1, C2 – collimator (focuser); AOC – acousto-optic cell; P – polarizer.](image)

To obtain the maximum intensity of the diffracted beam at the minimum ultrasonic wave power, the width of the sound column in the near zone of the ultrasonic wave (USW) transducer $H$ should be no less than the waist diameter $2w$: $H \geq 2w$. The speed of the modulator is characterized by the switching time $\tau$, that is, the time of power increase of the diffracted beam at a level from 0.1 to 0.9.

Of practical interest are AOMF in the Bragg mode at $a = \frac{\psi_{lgh}}{\psi_{snd}} \leq 1$, where $\psi_{lgh}$ and $\psi_{snd}$ are the divergences of light and sound beams, respectively, when a single diffraction order is formed and the maximum achievable diffraction efficiency value is $\geq 0.8$ [7]. In this case, the minimum switching time is proportional to the time of crossing the waist of the light Gaussian beam by the USW wavefront [7, 8]

$$\tau_{cr} = 0.64 \times \frac{2w}{V},$$  (1)
where \( V \) – USW speed. \( \tau \approx \tau_{cr} \) on condition
\[
(\Delta f_m, \Delta f_{af}, \Delta f_r) \gtrsim \Delta f_{cr} \approx 0.5/\tau_{cr},
\]
where \( \Delta f_{cr} \) – frequency switching band at the level of -3 dB (analog amplitude modulation bandwidth [7]), and all the bandpass frequency features of the real AOMF are listed in brackets: \( \Delta f_m \) – matching frequency band of the USW transducer with the RF transmission line (50 Ohm), within which the power of the control signal from the RF generator is transmitted to the USW transducer with losses \( \leq 3 \) dB [8, 9]; \( \Delta f_{af} \) – the width of the frequency instrumental function (frequency band of the AO interaction), inversely proportional to the length of the AO interaction, within which the diffraction efficiency is no less than 0.5 of the maximum value [9, 10]; \( \Delta f_r \) – reception frequency band, within which the power of the diffracted light beam is transmitted to the receiving fiber-optic cable with losses \( \leq 3 \) dB [11, 12].

If inequality (2) is not satisfied, \( \tau > \tau_{cr} \). A rough estimate of \( \tau \) can be made using the formula
\[
\tau = 0.5/\Delta f, \Delta f = \min (\Delta f_m, \Delta f_{af}, \Delta f_r, \Delta f_{cr}),
\]
where \( \Delta f \) – the frequency band of a real AOMF in the mode of the time front shaper of the intensity of the diffracted light, since the transmission coefficient of the system equals the product of the transmission coefficients of its components, and the pulse rise time \( \tau \) and the frequency band of harmonics \( \Delta f \), necessary for its formation are related by the ratio: \( \tau \times \Delta f \approx 0.5 \) [9].

Let the AOMF be used in the stationary frequency shifter mode to obtain the frequency shift of the diffracted light within the working band \( \Delta f = (f_0 + \Delta f/2) - (f_0 - \Delta f/2) \) [4]. In this case \( \Delta f_{cr} \) is not a limiting factor, and the ratio is true:
\[
\Delta f = \min (\Delta f_m, \Delta f_{af}, \Delta f_r).
\]

Let us note for the classical AOM with free light beams, there are no elements with a narrow angular field (except for the AOC itself), therefore, \( \Delta f_r \) is also not a limiting factor and (4) turns into: \( \Delta f = \min (\Delta f_m, \Delta f_{af}) \).

The figure 1(2) shows a scheme of a double-crystal AOMF (DAOMF) [13] as a broadband stationary frequency shifter, that consists of two identical AOC turned by 180°. In this case, the angle-frequency drift of the light beam after the first AOC is compensated for in the second AOC. As a result, the angular displacement \( \Delta \phi \) is converted into linear \( \Delta l \), and the direction of propagation and the state of polarization of the twice diffracted beam coincides with the direction and polarization of the input beam when the frequency of the control RF signal changes [14]. In DAOMF the “deflector” geometry of the AO interaction is used, when the USW wave vector touches the surface of the wave vectors of the diffracted radiation. In this case, \( \Delta f_{af} \) has a maximum for anisotropic diffraction, all conditions being equal [8, 10].

The matching band of the ultrasonic transducer (UT) \( \Delta f_m \) is determined by the values of the acoustic impedances of UT materials made of LiNbO₃ and a light-sound guide made of TeO₂ [9]. For used by us configurations of the AOC on the UT and the longitudinal USW in the isotropic diffraction mode, these values are close, which makes it possible to obtain an approximately octave UT matching band: \( \Delta f_m \approx 2f_0/3, f_0 \) – central frequency, i.e. at \( f_0 =100 \) MHz \( \Delta f_m \approx 66 \) MHz. For AOC on transverse USW in the anisotropic diffraction mode, the impedance values differ several times, and reaching the octave band \( \Delta f_m \) is associated with technological difficulties: it is necessary either to create antireflection layers between the UT and the AO crystal [8, 9], or to use conversion of initially excited longitudinal USW in the “working” transverse on a specially beveled face of the crystal [15].

The width of the frequency instrumental function for isotropic diffraction at the level -3 dB is [9]
\[
\Delta f_{af} \approx 1.77nV^2/(L\lambda f_0),
\]
where \( n \) – crystal refractive index, \( L \) – UT length along light propagation, \( \lambda \) – light wavelength in vacuum. The width of the frequency instrumental function of the anisotropic nonaxial deflector is [16]
\[ \Delta f_{af} \approx 2V \left( \frac{n}{\lambda L} \left( \frac{\Delta \Phi_e}{\pi} + \frac{\Delta \Phi_c}{\pi} \right) \right)^{1/2}, \]

where \( \Delta \Phi_{e,c} \) – permissible maximum phase mismatch at the edges of the instrumental function and at its center. For example, when \( \Delta \Phi = 0.799\pi \) the relative value of the instrumental function is \( T \approx 0.5 \), and when \( \Delta \Phi = 0.580\pi \), \( T \approx 0.7 \).

Values \( \Delta f_m, \Delta f_{af} \) are the key AOC characteristics; they do not depend on the design of the AOMF. On the contrary, \( \Delta f_r \) depends on both the details of the AO interaction and the AOMF device. Let's consider this characteristic in more detail.

3. AOMF design features limiting the frequency band

A specific feature of the AOMF shown in figure 1 is the availability of receiving a microlens with a narrow angular field, beyond which the intensity loss of the diffracted light beam increases sharply when entering the OF. The mechanism of the formation of the modulator reception band consists in limiting the aperture of the diffracted beam when it enters the receiving OF. In this case, for AOMF with collimators, the linear aperture is limited, and for AOMF with focusators - the angular aperture [11, 12]. The following expressions are obtained for the receiving frequency band at a level of 3 dB:

1) for single-crystal AOMF with collimators
\[ \Delta f_r \approx 0.8 \times V \times D / (\lambda \times F); \]  

2) for single-crystal AOMF with focusers
\[ \Delta f_r \approx 1.6 \times NA \times V / (M \times \lambda); \]

3) using the models and reasoning given in [11, 12], one can obtain a similar formula for the DAOMF band with collimators
\[ \Delta f_r \approx 1.6 \times NA \times V \times F / (\lambda \times \ell^*). \]

Here \( D \) – mode field diameter; \( F \) – focal distance of collimator; \( NA \) – numerical aperture of OF; \( M \) – AOMF optical system magnification; \( \ell^* = (\ell_1/\ell_1^* + \ell_2/\ell_2^* + \ell_3/\ell_3^*), \ell_{1,2,3} \) – path length of a twice diffracted beam in the crystals TeO₂, in polarizer and in the air, respectively, \( n_{1,2} \) – refraction indices of TeO₂ and polarizer material, respectively.

First thing to be noticed is that for all three variants the reception band is proportional to \( V \). Therefore, it is advisable to use isotropic diffraction on longitudinal USW, where the velocity \( V \) is much higher. To solve problems that require the widest possible working band, the optimal decision for a single-crystal AOMF is using a longitudinal wave with a wave vector along the Z-axis of the crystal. In this case \( V_{tg} = 4260 \text{ m/s} \), which is close to the maximum velocity of the longitudinal wave in TeO₂ (4600 m/s). This geometry of the AO interaction is unique as the diffraction efficiency for values close to unity does not depend on the state of polarization of the radiation. In addition, diffracted beams with mutually orthogonal polarization propagate at the output of the AOC in parallel and have the same optical losses when inputting the OF [4].

A distinctive feature of DAOMF is the fact that the resulting frequency shift of the light doubles. Consequently, \( \Delta f_m \) and \( \Delta f_{af} \) for a single AOC increase approximately two times for DAOMF. In this case, anisotropic diffraction on a transverse wave can be used. Features of anisotropic diffraction in TeO₂ – a radical (more than an order of magnitude) increase in the acousto-optical quality factor \( M_2 \) [8], as well as the need to work only with plane-polarized radiation. According to (9), \( \Delta f_{af} \) for DAOMF can be significantly increased by decreasing \( \ell^* \) using a thin-film polarizer instead of a crystalline one.

Since the DAOMF transfer coefficient is equal to the product of the transfer coefficients of two single AOC, to obtain the maximum band, it is important to align the centers of the bands \( \Delta f_m \) and \( \Delta f_{af} \), achieved by orienting AOC1 and AOC2 relative to the incident light beam.
4. Results of experimental studies and their discussion

Acousto-optic modulators/frequency shifters on TeO2 crystals with OF supporting and not supporting polarization for collimated and focused light beams at radiation wavelengths of 785, 1064, 1550 nm were produced and experimentally investigated. In the first three AOMF variants isotropic diffraction on a longitudinal USW propagating along the Z axis in the Bragg regime was used [11, 12]. For DAOMF, anisotropic diffraction with the geometry of AO interaction was used for a nonaxial anisotropic deflector [14]. The measurement results of the AOMF main parameters are summarized in table 1.

| AOMF name, design, type of OF | Wavelength, \(\lambda\), nm | Active aperture \(H\), mm | General optical losses, \(\alpha\), dB | Modulation contrast, \(K\) | Polarization contrast, \(K_p\), dB | Frequency range \(f_{\Delta} \pm 2\Delta f_k\), MHz | Switching time \(\tau\), ns | RF power, P, W |
|-----------------------------|--------------------------|--------------------------|---------------------------------|--------------------------|--------------------------|---------------------------------|--------------------------|--------------------------|
| Photon-6201 S, C, PM        | 1550±60                  | 1.6                      | -1.8                            | -56                      | -27                      | 80±2.6                          | 240                      | 2.9                      |
| 6202 S, C, SM               | 1550±60                  | 1.0                      | -2.0                            | -56                      | –                        | 110±2.7                         | 150                      | 1.9                      |
| Photon-6203 S, F, SM        | 1064±50                  | 0.12                     | -3.2                            | -63                      | –                        | 200±20                          | 18                       | 0.95                     |
| Photon-7201 D, C, PM        | 780±40                   | PM                       | -4.0                            | -33                      | –                        | 176±20                          | 1930                     | 0.25                     |

The first column contains the AOMF design features: S - single-crystal, D - double-crystal; C - with a collimated beam, F - with focusing the beam in the center of the sound column; PM - fiber that maintains the state of polarization (“Panda”), SM - fiber that does not maintain the state of polarization. In the second column, for the radiation wavelength, the spectral range is given, in which the reflection coefficient of the antireflection coating is < 0.2%.

The total optical losses were calculated by the formula: \(\sigma = 10 \log(I_{\Delta max}^{+1} / I_0)\), where \(I_{\Delta max}^{+1}\) - the maximum photoelectric signal value in «+1» diffraction order, \(I_0\) - the photoelectric signal value when the laser is connected to power meter by fiber optic cable, \(\lg - \) decimal logarithm. Optical contrast was calculated by the formula: \(K = 10 \log(I_{\Delta max}^{+1} / I_0)\), where \(I_{\Delta max}^{+1}\) - photoelectric signal value in «+1» diffraction order in the absence of the RF signal. Polarization contrast (for isotropic diffraction) is calculated by the formula: \(K_p = 10 \log(I_{\Delta max}^{+1} / I_0)\), where \(I_{\Delta max}^{+1}\) - maximum photoelectric signal value in «+1» diffraction order for radiation with polarization, orthogonal polarization of incident radiation. Switching time \(\tau\) was calculated by the formula (1). \(P\) is the power of the RF control signal, at which the value \(|\sigma|\) is minimum.

Table 2 shows the values of the AOMF bandpass frequency features.

| AOMF name | \(\Delta f_m^{exp}\), MHz | \(\Delta f_{af}^{calc}\), MHz | \(\Delta f_{af}^{exp}\), MHz | \(\Delta f_r^{calc}\), MHz | \(\Delta f_{cr}^{calc}\), MHz | \(\Delta f_{exp}^{exp}\), MHz |
|-----------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Photon-6201 | 40                       | 44                       | 45                       | 5.8                      | 2                        | 5.2                      |
| Photon-6202 | 55                       | 32                       | –                        | 5.8                      | 3.3                      | 5.4                      |
| Photon-6203 | 80                       | 95                       | 97                       | 36                       | 28                       | 41                       |
| Photon-7201 | 40                       | 88                       | –                        | 78                       | 0.3                      | \(\approx 40\)           |
Here $\Delta f_{m}^{\text{exp}}$ – the UT matching band, measured by the level of voltage standing wave ratio VSWR = 3; $\Delta f_{\text{calc}}^{\text{exp}}$ – width of the frequency instrumental function, calculated by the formulas (5), (6); $\Delta f_{af}^{\text{exp}}$ – width of the frequency instrumental function, measured with the installed input focuser (collimator) C1 without receiving focuser (collimator) C2. In this case a wide-aperture photoreceiver with an angular aperture $\Delta \alpha \gg 2NA/f \approx 0.7^\circ$ [12] was installed directly behind the AOC; $\Delta f_{\text{calc}}^{\text{exp}}$ – width of reception frequency band, calculated by formulas (7) - (9); $\Delta f_{\text{exp}}^{\text{calc}}$ – the switching frequency band, calculated by equations (1)-(2); $\Delta f^{\text{exp}}$ – working frequency band measured with the installed focusers (collimators) C1, C2.

It follows from the analysis of the table:
1. When the AOMF operates as an amplitude modulator, the inequality (2) is valid.
2. When the AOMF operates in a stationary frequency shifter mode, the inequality (4) is valid.
3. Focused light beam scheme gives a radical broadening of the reception band [12].
4. For AOMFs Photon-6201 and Photon-6203 there is a good agreement between the calculated $\Delta f_{\text{calc}}^{\text{exp}}$ and measured values of the reception band $\Delta f^{\text{exp}}$, which indicates the adequacy of the adopted models of the mechanisms for the formation of the AOMF reception band [11, 12].
5. Experimental data for DAOMF Photon-7201 do not allow estimating the band $\Delta f^{\text{exp}}$, as $\Delta f^{\text{exp}}$ in this case is limited by the ratio:

$$f^{\text{exp}} \leq \min \{\Delta f_{af}^{(1)\text{calc}} \approx 51 \text{ MHz}, \Delta f_{\text{calc}}^{\text{exp}} \approx 78 \text{ MHz}, \Delta f_{m}^{(1)\text{exp}} \approx 40 \text{ MHz}\} \approx 40 \text{ MHz},$$

where $\Delta f_{af}^{(1)\text{calc}}$ and $\Delta f_{m}^{(1)\text{exp}}$ relate to a single AOC. At the same time, it can be seen that the value $\Delta f_{\text{calc}}^{\text{exp}}$ for DAOMF significantly exceeds the corresponding values for single-crystal AOMF.

### 5. AOMF implementation possibility with minimum switching time

The question arises: what factor limits the minimum switching time in the AOMF? In works [11, 12], estimations are made of the minimum values of the AOMF switching time $\tau_{\text{min}}$, based on the maximum value of the acoustic power density limited by the electrical breakdown of the UT. Table 3 summarizes the parameters calculated by formulas (1)-(8) with account for the data [11] and the values of the maximum acceptable acoustic power density in the pulsed mode $\rho_{\text{imp}} \approx 360 \cdot 10^8 \text{ W/m}^2$.

| $\lambda$ (nm) | $L$ (µm) | $H$ (µm) | $f_0$ (MHz) | $\tau_{\text{min}}$ (ns) | $\Delta f_{cr}^{\text{calc}}$ (MHz) | $\Delta f_{m}^{\text{calc}}$ (MHz) | $\Delta f_r^{\text{exp}}$ (MHz) | $\Delta f_{af}^{\text{exp}}$ (MHz) | $P_a$ (W) | $m$ |
|----------------|---------|---------|-------------|----------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|--------|-----|
| 1064           | 225     | 14.6    | 455         | 2.2            | 227                           | 303                           | 650                           | 205                           | 451    | 2.5 |
| 1550           | 323     | 21.2    | 313         | 3.2            | 156                           | 209                           | 205                           | 451                           | 2.5    | 2.5 |

The matching band of the UT was assumed to be equal to an octave, that is, $\Delta f_m = 2f_0/3$. The last column of table 3 shows the minimum values of the period to the “time on” ratio for the pulse sequence of the control RF signal $m$, at which the time-average power $< P_a >$ does not exceed the “safe” level of 1 W for the thermal mode of the UT.

Table 3 shows that inequality (2) is satisfied for both radiation wavelengths of 1064 nm and 1550 nm. This allows us to assert that the scheme with a focused beam makes it possible to realize AOMF with $\tau$ close to the limiting values $\tau_{\text{min}}$, limited by the breakdown voltage of the used UT.

The developed devices can be used in various applications: 1) for increasing the range of amplitude and frequency modulation of lasers with fiber optic outputs; 2) for pulse selection in fiber systems with a high repetition rate to increase the repetition rate range; 3) for creation of transportable optical and microwave frequency standards [4] to decrease their dimensions; 1) for increasing sampling resolution in fiber-optic sensors and range finders [17].

### 6. Conclusions

Acousto-optic modulators/shifters based on TeO$_2$ crystals with single-mode optical fibers supporting and not supporting polarization for collimated and focused light beams at radiation...
wavelengths of 785, 1064, 1550 nm have been developed, produced and experimentally investigated. The mechanisms of formation and methods of expanding the working band of the modulator are determined. Expressions for the AOMF reception frequency band are obtained for various designs. An AOMF with beam focusing and switching time $\approx 18$ ns was produced, and its experimental parameters were determined. Calculated and measured values of the receiving frequency band are in good agreement. A double-crystal acousto-optic laser radiation frequency shifter with a working bandwidth of $\approx 40$ MHz has been created. Single-crystal modulators based on collimated beams with a frequency band of $\approx 10$ MHz are experimentally investigated. It is shown that focusing of the light beam at the center of the sound column makes it possible to implement a modulator with a minimum switching time of $\approx (2-3)$ ns. This value is limited by electrical breakdown of the ultrasonic wave transmitter.

References
[1] Antonov S N 2019 JhTF 89(2) 274-9
[2] Berdasov O I, Gribov A Yu, Strelkin S A and Slyusarev S N 2017 Almanac of Modern Metrology 11 81-94
[3] Kupalov D S, Baryshev V N, Blinov I Yu, Boiko A I, Domnin Yu S, Kopylov L N, Kupalova L N, Novoselov A V and Khromov M N 2017 Almanac of the Modern Metrology 11 95-103
[4] Epikhin V M, Baryshev V N, Slyusarev S N, Aprelev A V and Blinov I Yu 2019 Quantum Electronics 49(9) 857-62
[5] Blistanov A A, Bondarenko V S, Perelomova N V and Shaskolskaya M P 1982 Acoustic Crystals (Moscow: Nauka)
[6] Aikhler Y and Aikhler G 2012 Lasers. Execution, Management, Application (Moscow: Technosphera)
[7] Maydan D 1970 IEEE J QE-6(1) 15-8
[8] Magdich L N, Molchanov V Ya 1979 Acousto-optical Devices and Their Application (Moscow: Sov. Radio)
[9] Dielesan E and Royer D 1982 Elastic Waves in Solids. Application for Signal Processing (Moscow: Nauka)
[10] Balakshy V I, Parygin V N and Chirkov L E 1985 Physical Foundations of Acousto-optics (Moscow: Radio and communication)
[11] Epikhin V M and Karnaushkin P V 2020 Quantum Electronics 50(10) 962-6
[12] Epikhin V M and Ryabinin A V 2021 ZhTF 91(6) 1021-5
[13] Mazur M M, Mazur L I and Shorin V N 2017 Double-crystal acousto-optic Frequency shifter Patent RUS 2648567 24.05.2017
[14] Mazur M M, Mazur L I, Ryabinin A V and Shorin V N 2020 Quantum Electronics 50(10) 954-65
[15] Gusev O B and Kludzin V V 1987 Acousto-optical Measurements (L.: LSU Publishing House)
[16] Gazelet M G, Carlier S, Picault J P, Waxin G and Bruneel C 1985 Appl Opt 24(24) 4435-8
[17] Lukashova T O, Naniy O E, Nikitin S P and Treshchikov V N 2020 Quantum Electronics 50(9) 882-7