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Finite-difference time-domain simulation of compact acousto-optic filters based on multireflection beam expanding

A.V. Tsarev

***Abstract*. The results of numerical simulation of acousto-optic (AO) tunable filters of a new type based on multireflection beam expanding in waveguide structures are discussed. Planar waveguide filters based on thin chalcogenide (As_2S_3) films of lithium niobate ($LiNbO_3$) are considered. The operation of filters is analysed by the finite-difference time-domain (FDTD) method by using the license FullWAVE software package (RSoft Design Group, Inc.). It is shown that AO filters have very good dispersion properties and AO filters of extremely small size provide a narrow filtration line within the tuning range of more than 100 nm (at a wavelength of 1.54 μm). It is important that the normalised linewidth (measured in units of the reciprocal filter length) is an order of magnitude smaller than the theoretical limit for AO filters produced from the same material in the conventional way, without the use of multireflection beam expanding.**

Keywords: *integrated optics, optical waveguides, acousto-optic tunable filter, surface acoustic waves, multireflection beam expander.*

1. Introduction

To satisfy the increasing need in broadband and high-data-rate communications in fields of Internet, video-on-demand (VoD), telemetry, etc., tunable optical filters and optical add/drop multiplexers (OADMs) with high technical parameters are required. They allow the efficient use of broad transmission bands of optical fibres and provide the great flexibility and possibility of the operation of commuting modules without intermediate conversions of optical signals to electric signals and vice versa. The efficiency of modern wavelength-division-multiplexing (WDM) fibreoptic communication lines (FOCLs) can be increased by increasing both the bit rate in an individual spectral channel and the number of parallel spectral channels [1].

To increase the bit rate from 2.5 Gbit/s up to 10, 40 or even 160 Gbit/s, it is necessary to decrease the duration of transmitted optical pulses and increase their peak power. In turn, this enhances the influence of dispersion and nonlinear effects during the propagation of a short pulse in a long optical fibre. To suppress these effects or reduce their role, it is necessary to use high-cost G-655 optical fibres with the nonzero shifted dispersion together with additional dispersion compensators. Note that in fibreoptic networks over the world (including Russia), relatively cheap standard single-mode G-652 fibres are mainly used which account for 90 % of the total worldwide fibre market. However, the dispersion of these fibres is four times higher than that of high-cost G-655 fibres accounting only for 3.5 % of the worldwide fibre market [2]. Therefore, a further increase in the transmission efficiency of FOCLs by increasing the bit rate is difficult to realise and expensive at present.

The well-known and more economical alternative solution is a considerable increase (by more than 200 times) in the number of spectral channels in communication lines by using WDM [1]. An additional argument in favour of this solution was put forward by the management of Fujitsu (Japan) [3]. Their analysis of the worldwide demand in data transfer (obeying the Moor law) showed that due to excessive energy expenditures for controlling ever increasing data flows transmitted over fibreoptic networks, the available technologies are insufficient for their successful development (even based on economical considerations). The solution of this problem will require the cardinal change in the FOCL architecture, for example, based on virtual flexible routing devices [3], in which up to 1000 different wavelengths will be used in one fibre in the future.

Although numerous different technologies and concepts have been proposed for the development of tunable optical elements for FOCLs [1], neither of them can be considered ideal and having potency for replacing all the others in the nearest future. Therefore, the development of new types of tunable optical devices for controlling many hundreds of frequency channels is still of current interest.

The strategy of some researchers [4 – 6] is based on the use of acousto-optic (AO) tunable filters and multiplexers, which offer a number of natural advantages such as a very broad tuning band and a fast response (several microseconds), a great flexibility and the unique capability of dynamic filtering and redirecting simultaneously several spectral channels to a single fibre by using acoustic waves at several frequencies, which are different in different channels.

However, the bandwidth of the known AO filters is limited (usually by 1.6 nm) due to objective physical factors such as the dispersion properties and size of AO elements, as well as structural features of filters. The necessity of

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A.V. Tsarev Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, prosp. akad. Lavent'eva 13, 630090 Novosibirsk, Russia; e-mail: tsarev@isp.nsc.ru

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increasing the number of spectral channels inevitably complicates the filter design because standard AO elements operate already now near their theoretical limit, and the improvement of the frequency resolution is achieved only by using additional interleavers [5] or by cascading (combining several sections) separate AO elements [4, 6]. In particular, by using a uniquely complicated technology, researchers at Fujitsu have combined three series-connected AO elements to fabricate a tunable AO filter/multiplexer based on strip lithium niobate waveguides of length 7 cm with the record narrow bandwidth of 0.37 nm at a wavelength of 1.54 μm [6]. This provides the operation of the multiplexer with 32 frequency channels with a step of 0.8 nm.

In this paper, a new type of AO filters [7, 8] based on multireflection beam expanders (MRBEs) [9, 10] is discussed. These filters offer promise for the bandwidth narrowing by an order of magnitude [11, 12] and the reduction of the size and increasing the fast response of devices. The results of numerical simulation of AO devices in planar waveguides based on thin chalcogenide glass (As_2S_3) on lithium niobate ($LiNbO_3$) are presented. The operation of AO devices is analysed in numerical experiments by the finite-difference time-domain (FDTD) method by using the license FullWAVE software package (RSoft Design Group, Inc.).

The MRBE optical elements attract interest because, having a very small size (less than 1 cm), they possess specific dispersion properties providing the record narrow (0.1 nm) filtration line [11, 12] at a wavelength of 1.54 μm within the tuning bandwidth more than 40 nm with the switching time less than 2 μs. Thus, these elements pretend to a free vacancy of the base construction for low-cost narrowband tunable filters and multiplexers for wide applications.

2. Simulation of AO filters by the FDTD method

Tunable MRBE filters are new and unobvious optical elements, which have not been completely described theoretically so far, and the methods of numerical simulation of these filters are developed insufficiently. Our preliminary analysis [11, 12] based on the spectral approximation showed that these devices possess unique filtering properties. The alternative approach involves model numerical experiments by the FDTD method. The FDTD simulations of optical filters and multiplexers containing several closely spaced MRBEs [13] confirmed the correctness of the new idea of filtering and multiplexing. However, these calculations cannot predict the behaviour of the AO filter under conditions of the acousto-optic control of the filtration wavelength. Below, the results of the FDTD numerical simulation of tunable MRBE AO filters are discussed for the first time.

The operation principle of MRBE AO filters is based on the multiple-beam interference and diffraction of light from a surface acoustic wave (SAW) in optical waveguides. It can be illustrated by the example of an AO filter shown in Fig. 1. The filter is made of a thin (~ 1.5 μm) chalcogenide glass layer deposited on the surface of a lithium niobate substrate required for efficient excitation of SAWs with the help of an interdigital transducer. Strip waveguides of width W fabricated in the chalcogenide glass film are oriented so that the optical modes of strip waveguides are not connected with the planar waveguide region. Multireflection beam expanders are fabricated in strip waveguides by an electron beam writing inclined semi-transparent strips (elementary reflectors) of thickness D with a step of d. Their optical properties are slightly changed to provide the weak reflection of an optical beam with low losses to the side – from the strip waveguide to the planar one.

The beam expander is based on the multiplexing of the optical field of the guided mode on many semi-transparent inclined elementary reflectors [9, 10]. For this purpose, a narrow optical beam is coupled to a strip optical waveguide of the first beam expander and is split into two beams in each of the elementary reflectors. One of the beams (of considerably lower intensity) after reflection is directed from the strip optical waveguide to the planar optical waveguide, while the other (main in intensity) passes thorough the strip waveguide to the next elementary reflector, in which it is split again into two beams, etc. All the reflected beams are summed coherently taking into account the optical phase shift caused by the delay of the light beam on the interval between adjacent reflectors. The resulting light beam at the MRBE output has a wide aperture (exceeding the input aperture by hundreds and thousands times) and a low divergence. In addition, the direction of this beam con-

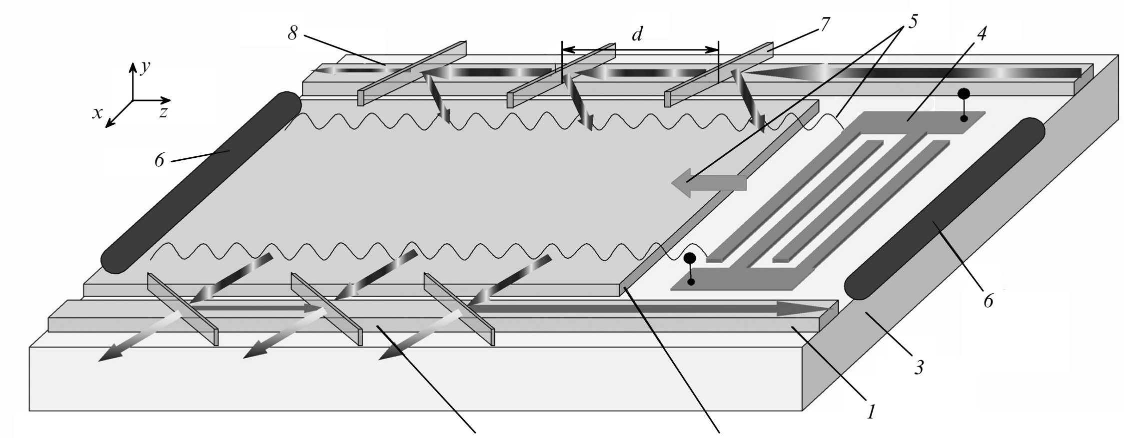

Figure 1. Noncollinear AO filter based on multireflection beam expanders: (*1*) strip waveguide; (*2*) planar waveguide; (*3*) piezoelectric substrate; (*4*) interdigital transducer; (*5*) SAW; (*6*) SAW absorber; (*7*) elementary reflector; (*8*) first beam expander; (*9*) second beam expander.

tinuously changes when the radiation wavelength is changed monotonically, i.e. the proposed beam expander has strong dispersion properties.

Then, the expanded beam diffracts in the planar waveguide plane from a SAW, the angle of diffracted radiation being synchronously changed according to the Bragg condition in a broad range with changing the SAW frequency. The diffracted and non-diffracted optical beams emerging from the acousto-optic interaction region intersect the second beam expander representing a strip waveguide with a set of similar elementary reflectors, which operates with respect to the input beam expander as a reversible optical element. Namely, optical microscopic beams of only a certain wavelength and direction, collected by elementary reflectors of the second waveguide, are summed coherently with each other and emerge from the strip optical waveguide as the intense narrowband signal. For all other wavelengths, the condition of coherent interference will be violated, and the resulting field from different reflectors at the output of the strip optical waveguide will be close to zero. As the SAW frequency is changed, the direction of the beam incident on the second beam expander changes, and therefore, the wavelength of light, for which the efficient filtration is performed, can be easily tuned. In this case, high dispersion properties of the beam expander allow one to obtain the anomalously narrow, earlier inaccessible filtration line for a small (less than 1 cm^2) area of the filtering element [11, 12].

It is known that the three-dimensional numerical simulation of light propagation requires huge computational resources. Despite a small size ($\sim$ 1 cm) of optical filters, they contain hundreds of mutually interfering light microfluxes, which prevents the analysis of large three-dimensional structures. In this paper, to reduce the computation time, three-dimensional waveguide structures are replaced by their two-dimensional analogues by using the method of effective refractive index [14]. In this case, the TM mode of the strip waveguide corresponds to the TE mode of the equivalent planar waveguide. This approach can be used when elementary reflectors completely overlap the aperture of the guided mode in the transverse direction (inside the waveguide). In this paper, AO filters were simulated by the FDTD method by using the commercial FullWAVE software package specially developed by RSoft Design Group Inc. [15] for problems of integrated optics and photonics. The action of SAWs was simulated by an equivalent stationary refractive-index diffraction grating.

At the first preliminary stage, the classical problem of the propagation and diffraction of an optical beam from a sinusoidal diffraction refractive-index grating was simulated. The total field inside an optical element and the far-field radiation distribution were calculated numerically. The diffraction efficiency was found by the relative maximum intensity of the spectrum of the transmitted wave with respect to the case without the diffraction grating. It is known that the maximum diffraction efficiency for a Bragg grating in the case of phase matching (light is incident at the Bragg angle θ) should be observed at the modulation depth dn of the refractive index determined by the expression

$$dn = \lambda_0 \cos\theta/(2L). \tag{1}$$

Calculations performed for the wavelengths $\lambda_0 = 1.5486$ μm, the aperture $L = 50$ μm, and the grating period $\Lambda = 1.3$ μm gave the value $dn = 0.0147$, which differs from (1) by 3 %. This confirms the applicability of the FDTD method for solving Bragg diffraction problems by using a large step (0.05 μm) of the calculation network. This is very important for further analysis because a decrease in the step leads to considerable computational difficulties since the random-access memory and computation time required for solving two-dimensional problems increase approximately as the cube power of the ratio of the characteristic size of the structure to the simulation step.

The next preliminary stage involves the study of the propagation of the TE and TM guided modes through an inclined reflector at different angles of incidence for different thicknesses and refractive indices of the reflecting strip forming an elementary reflector. Typical dependences of the reflection coefficient R on the reflector thickness D are presented in Fig. 2. Hereafter, all numerical calculations will be performed for the fundamental TE guided mode propagating in a planar waveguide.

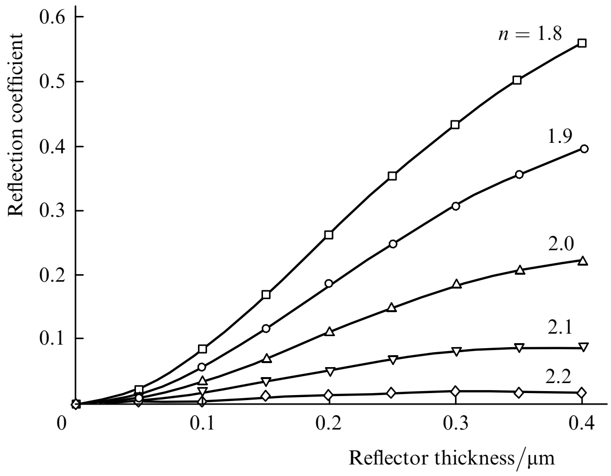

Figure 2. Dependences of the power reflection coefficient on the reflector thickness for different refractive indices n of the reflecting strip and the angle of incidence of 52.5°.

Having performed preliminary calculations, we can now simulate real filters with beam expanders. Based on our computational possibilities and expediency considerations, we analysed an optical filter with beam expanders containing 32 identical elementary reflectors each with a step of 4.6 μm (Fig. 3). Note that the size of this filter is sufficient for the basic properties of the optical elements to be manifested explicitly. In particular, it is very important that the parameters of the diffraction grating correspond to the Bragg regime providing the high diffraction efficiency (99.2 %) and also the presence of only one diffraction maximum.

The qualitative description of the operation of the tunable MRBE AO filter allows us to formulate general requirements providing the proper operation of the filter. The angular spectrum of the output radiation contains, except the fundamental spectral component, the side satellites with smaller amplitudes (Fig. 4), which can give rise to parasitic signals at the AO filter output. Therefore, the combinations of parameters (period and the reflector inclination angle, the SAW wavelength, etc.) of the AO filter will be optimal for its operation, if they suppress, on the one hand, the leakage of the parasitic signal, i.e. the

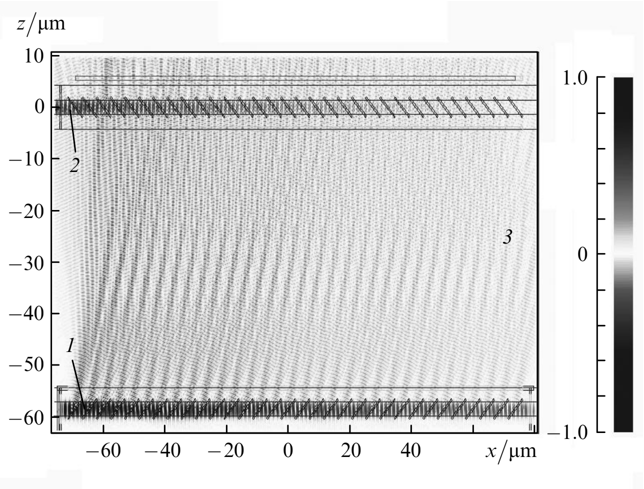

Figure 3. Propagation of optical waves in an optical filter with a diffraction grating and two beam expanders with 32 elementary reflectors. The FullWAVE calculation [15] with a step of 0.06 μm for $L =$ 50 μm, $\Lambda = 1.3$ μm, $W = 3.8$ μm, $d = 4.6$ μm, $D = 0.39$ μm, and $\lambda_0 =$ 1.5486 μm [(*1*) input of the first beam expander; (*2*) output of the second beam expander; (*3*) diffraction grating produced by a SAW].

coaxial alignment of the radiation patterns of the spectral components of each of the beam expanders is excluded, and on the other hand, provide the efficient filtration at the acoustic wave. Note that these requirements should be fulfilled over the entire tuning range of the optical filter within the so-called free spectral range. It will be shown below that for the reflection period $d = 4.6$ μm, the filter operation within the standard wavelength range 1.528 – 1.565-μm (the C band) can be easily provided.

Figure 4 shows the FDTD simulation of the angular spectrum of the device in the presence and absence of a diffraction grating produced by a SAW. In the absence of a SAW ($dn = 0$), the angular spectrum of the beam expander exhibits the main peak making the angle $\theta = 14.9°$ with the diffraction-grating grooves and two side peaks of lower intensities at angles $\theta = 6.5°$ and 23.9°. This spectrum is typical for the phase diffraction grating of the Michelson echelon type and is the result of multiplication of two factors. The first of them describes the angular spectrum of a limited light source formed upon partial reflection of the guided mode of a strip optical waveguide. The spectrum has a broad (~ 10°) angular distribution with the maximum corresponding to the specular reflected beam ($\theta = 14.9°$). The second factor describes a narrow line spectrum with the angular divergence ~ 0.25° and describes the result of interference of optical waves reflected from different elementary reflectors. The line positions in the line spectrum are determined by the condition of constructive interference to the corresponding diffraction orders, which are located with an angular step of about 9°. In our case, the tilt of the reflectors is chosen so that specular reflected beams propagate at angles close to the Bragg angle (at the central frequency of the AO filter). For this reason, only one main and two side diffraction peaks are observed in Fig. 4.

In the presence of the SAW-induced diffraction grating with the optimal amplitude ($dn = 0.0147$) and period $\Lambda = 1.3$ μm, the Bragg conditions are fulfilled only for the main peak, and the greater part of its energy is transferred to the angular range $\theta = -14.9°$ to be subsequently efficiently filtered in the second beam expander (see Fig. 1). In this case, the two side satellites almost will not change their amplitudes and will pass through the second beam expander, their angular position also being invariable. If, by varying the SAW frequency, we change the wavelength Λ (i.e. the diffraction grating period), the Bragg conditions will be also fulfilled only for the main peak, but already for different wavelength of light, at which the efficient filtration will be observed.

This is illustrated in Fig. 5 where the filtration efficiency, i.e. the intensity ratio of the output signal of the second beam expander to the input signal of the first beam expander is shown for different SAW wavelengths. One can see that the device of size 150 × 70 μm provides the tuning of filtered radiation within 100 nm with the linewidth 4.5 nm by varying the SAW wavelength from 1.1 to 1.4 μm. Note that for $\Lambda = 1.5$ μm, the device also efficiently filters optical radiation; however, in this case a parasitic signal is observed within the tuning band of the optical filter. Therefore, it is meaningless to change the SAW wavelength more than

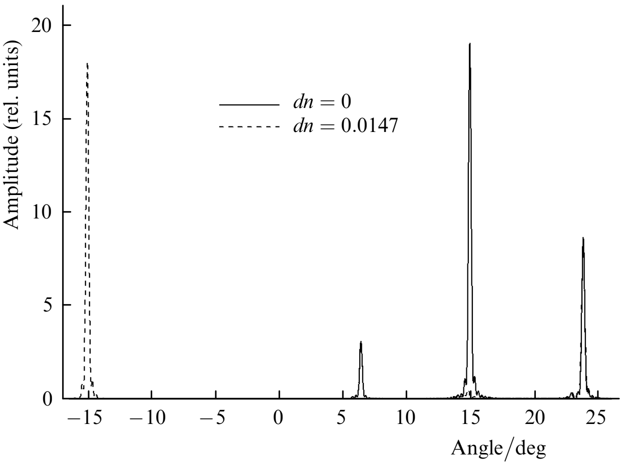

Figure 4. Angular spectrum of the optical beam formed by a beam expander after propagation through a Bragg grating with different modulation depths *dn*. The FullWAVE calculation [15] with a step of 0.05 μm for $L = 50$ μm, $L = 1.3$ μm, $W = 3.8$ μm, $d = 4.6$ μm, $\lambda_0 =$ 1.55 μm, and $\theta = 14.87°$.

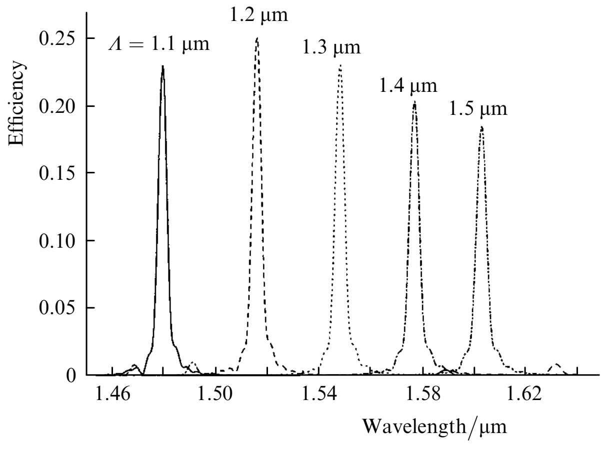

Figure 5. Filtration efficiency of the optical filter with a diffraction grating and two beam expanders with 32 elementary reflectors. The FullWAVE calculation [15] with a step of 0.05 μm for $L = 50$ μm, $W = 3.8$ μm, $d = 4.6$ μm, $D = 0.39$ μm, $\Delta\lambda = 4.5$ nm.

necessary to provide tuning within the free spectral range. In our case, for $d = 4.6$ μm, the free spectral interval is 109 nm; here, it is determined as the difference of wavelengths corresponding to the propagation of the working and parasitic signals in the tuning band of the optical fibre.

The FDTD simulations conclusively prove the validity of the concept used for the development of tunable MRBE AO filters. These simulations yield information that can be used to analyse similar AO elements in the spectral approximation [12], in particular, they allow one to describe quantitatively the properties of inclined elementary reflectors depending on their parameters.

Our analysis revealed a number of important properties of MRBE AO filters. The diffraction efficiency from a SAW for a set of beams formed by the beam expander is similar to the classical diffraction of a light beam with the equivalent total aperture and is characterised by the same optimal value of the modulation depth dn of the refractive index. As a whole, the operation of the AO filter is well described by the behaviour of the angular spectrum of the beam expander.

To reduce the required computational resources, we simulated filters for a small spacing period of reflectors ($d = 4.6$ μm). This provides the tuning range of the AO filter more than 100 nm. For most practical applications, the free spectral range of width 40 nm is sufficient. Therefore, the values of d and Λ can be increased by a factor of 2.5 by preserving all the positive functions of the filter. In this case, the AO filter of size 600 × 300 μm with the same 32 reflectors will provide the filtration linewidth of 1.8 nm and tuning within 40 nm upon varying the SAW wavelength from 2.75 to 3.5 μm.

It is known that the frequency resolution of an AO filter improves with increasing its size. Therefore, it is convenient to compare the possibilities of different AO technologies in terms of the specific linewidth measured in units of the reciprocal length of the filter. The AO filter proposed here has the uniquely narrow specific linewidth equal to 0.7 μm^2 (0.07 nm cm). This allows the construction of AO filters with the linewidth of 0.1 nm and smaller, which cannot be in principle achieved in AO filters of other types [4, 6], which have much greater dimensions and, hence, their response, determined by the travel time of an acoustic wave through the AO interaction region, is slower.

However, the parameters of the AO filter shown in Fig. 1 strongly depend on the incident radiation polarisation. This is explained both by the difference between the reflection coefficients of elementary reflectors for the TE and TM waves of the optical waveguide and the anisotropy of light diffraction by SAWs. In most practical applications, the polarisation-independent devices are required. This goal can be achieved by using two identical AO filters together with two polarisation splitters and two polarisation rotators (TE ↔ TM) (Fig. 6). The input optical signal is divided into two polarised signals (TE and TM), then the TE polarisation is transformed to the TM polarisation and both channels are simultaneously processed by two identical AO filters. One of the beams at the filter output experiences optical rotation (from the TM to TE polarisation) and all the filtered signals are again combined to one beam in a similar polarisation splitter, which serves as a polarisation combiner. It is important that all these elements can be realised on one lithium niobate substrate and, hence, the filter will be both compact and stable.

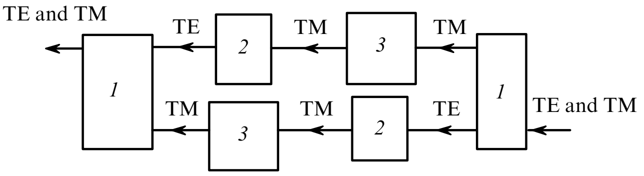

Figure 6. Structure of polarisation-independent acousto-optic filter: (*1*) polarisation splitter; (*2*) polarisation rotator; (*3*) acousto-optic filter.

3. Conclusions

Multireflection beam expanders and new types of tunable AO filters based on them have been numerically simulated by the FDTD method. Simulations have been performed for the model waveguide structure consisting of a thin chalcogenide glass on the surface of lithium niobate. This structure is of interest because optical elements can be simply fabricated in it by direct electron-beam writing. To reduce the calculation time, three-dimensional waveguide structures were replaced by their two-dimensional analogues and the influence of an acoustic wave was simulated by means of the equivalent stationary refractive-index grating.

The numerical FDTD experiments have revealed the basic properties of AO filters and confirmed the validity of the general concept of fabricating AO filters by using multireflection beam expanders. In particular, the tuning within 100 nm with the 4.5-nm linewidth of the AO filter of size 70 × 150 μm^2 has been demonstrated. The uniquely narrow specific linewidth of 0.7 μm^2 (0.07 nm cm) allows the manufacturing of AO filters having the resolution of 0.1 nm and better, which cannot be obtained for AO filters of other types.

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