Appl. Phys. B 73, 495–498 (2001)
DOI: 10.1007/s003400100703

Applied Physics B
Lasers and Optics

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A new type of small size acousto-optic tunable filter with super narrow optical linewidth

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Received: 28 April 2001/Revised version: 22 August 2001
Published online: 2 November 2001 •

ABSTRACT The new concept of the creation of an acousto-optic tunable filter (AOTF) with super-resolution and small size is discussed. The advantage of the device is based on the use of a novel type of multi reflector beam expander that produces a highly collimated optical beam (angular spread about 100 ppm), tilted with a change in optical wavelength. The proposed AOTF, 1 cm in length, can have an optical linewidth about 0.1 nm and up to 400 tunable channels at a wavelength of 1540 nm. It can be utilized as a tunable filter for dense wavelength-division multiplexing (DWDM) in fiber optic networks and as a small-sized tunable optical spectrometer, for example, in sensors of gases, liquids and solids. The acousto-optic tunable filter can be developed by known technology developed for the creation of integrated optics and microelectronics devices.

PACS 42.79.C; 42.79.F; 42.79.G; 42.79.J; 42.79.S; 42.82.E

1 Introduction

The recent forecasts of the experts [1] regarding the market for optical network systems for the next seven years show that most development will occur in systems based on dense wavelength-division multiplexing (DWDM). Optical add/drop multiplexer (OADM) components form the basis of such systems. Components include demultiplexing filter modules, passive optical combinations, optical switches, optical amplifiers, receivers and transponders, where applicable. The global consumption of OADM components in 1998 is estimated to be \$ 9.5 million. This figure will rise rapidly to \$ 534 million in 2003. Strong growth will then continue, averaging 59% per year, to reach \$ 5.35 billion by 2008 [1].

One of the most promising areas is the use of the spectral range of 1528.77 to 1569.59 nm, which is within the current optical amplifier window and within the window of minimum optical loss for optical fibers. At a channel spacing of 100 GHz (0.8 nm), the given transmission window (5.1 THz) allows 51 different wavelength channels, while a spacing of 25 GHz (0.2 nm) allows for 204 channels. By using the L-band (up to 1612.65 nm), one can double the number of transmitted channels.

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Thus, the development of DWDM optical units for fiber-optic networks with a super narrow linewidth (less than 12 GHz) is an urgent task. The best variants of such units will form a basis for the rich market for optical networks for the coming years.

2 Description of the concept

Until now, one of most promising areas for DWDM systems have been acousto-optic (AO) tunable filters based on the collinear diffraction of light by a surface acoustical wave (SAW) in strip optical waveguides [2–4]. It is possible to show that the optical linewidth of the collinear acousto-optic tunable filter (AOTF) is given by the expression:

$$\delta\lambda = A\lambda^2/\Delta NL \,, \tag{1}$$

where A is a numerical coefficient (about unity) depending on the construction of the filter, $\delta\lambda$ is the optical linewidth, λ is the optical wavelength in vacuum, ΔN is the difference in effective refractive indices for guided waves of different polarization, L is the AO interaction length. A collinear AOTF has not enough narrow optical linewidth, which is limited by the value of optical anisotropy and the interaction length and cannot be reduced without essential increase of the device size, and, therefore, increase in switching time between the channels. The main parameters of some main types of AOTFs are shown in Table 1. One can see that even for the best known device developed by Fujitsu Laboratories Ltd. the optical linewidth is about 0.37 nm for a device of 8 cm length [4].

In this paper, the essentially new concept [5, 6] of the creation of an acousto-optic tunable filter is proposed. The principal view of the device is shown on Fig. 1. It contains monomode planar and strip waveguide structures, an interdigital transducer (IDT) for excitation of surface acoustic waves (SAW) and a novel type of optical beam expander (BE) [7] that further evolves the fruitful idea of grating beam expanders [8, 9]. The description of the work of the BE will be described in a patent application [7] and another paper, but some general features of it can be listed below.

Let the optical beam of multiple wavelengths within a spectrum range $\Delta\lambda$ come from the input fiber 1 to the input strip waveguide. It then passes through an optical beam expander that contains an array of multiple partially reflecting mirrors. These extend the optical beam and deliver it to

Paramenter/Developer	Paderborn University [3]	Fujitsu [4]	Tsarev [5]
Material	Ti:LiNbO$_3$	Ti:LiNbO$_3$+In:SiO$_2$	Ti:LiNbO$_3$
Number of stages	2	3	1
Optical tuning mechanism	Collinear diffraction by SAW	Collinear diffraction by SAW	Noncollinear diffraction by SAW
Sample/AO length	7 cm/1.9 cm	8 cm/4 cm	1 cm /0.7 cm
3 dB linewidth	1.6 cm	0.37 cm	0.1 cm
Tunable range	70 nm	26 nm	40 nm
Number of tunable channels (3 dB)	44	70	400

TABLE 1 Comparison of the main types of AO tunable filters

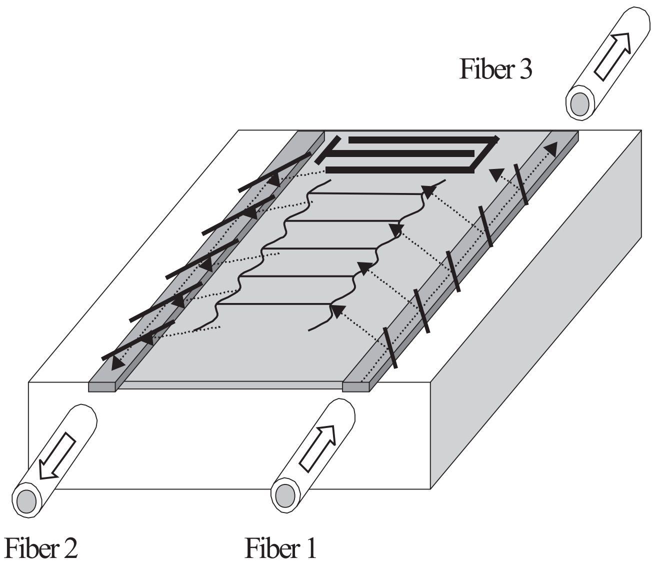

FIGURE 1 Principal view of the AOTF with super-resolution

a planar optical waveguide. The efficiency of the transformation depends on device parameters and on optimal conditions and can be as much as 50%–90% [6]. Then, the expanded optical beam arrives at the area of acousto-optic interaction and diffracts by SAW. The second beam expander works as a reciprocal optical element. It can transform the wide optical beam to the output, fiber 2. However, it picks up only those optical beams that have every desired optical wavelength and which have the proper designed direction of propagation, depending on the parameters of the beam expander. Due to Bragg conditions, by changing the SAW frequency one can change the direction of propagation of the diffracted beam and thus tune the optical wavelength that is dropped by the AOTF [5, 6]. The untransformed part of the incident beam arrives at output fiber 3 and can be used for input signal control or can pass to other optical elements.

3 Results and discussions

The quantitative descriptions of the BE and AOTF are very complicated, but some reasonable quantitative estimates can be done by simple and evident approximation analysis. Let $U(p)$ describe the tunable properties of the AOTF in the terms of the angular spectrum of the BE. It represents the spectrum of a phase diffraction grating, and can be found by standard procedure [10]. As usual, the light is incident on the reflector array at close to the Brewster angle. For this reason, the throughput signal for the TE wave is essentially reduced in comparison to the TM wave, and is not taken into account. For the simplicity, let describe lateral distribution of electric field of guided fundamental TM-mode as $\exp(-(y/\omega_0)^2)$, where ω_0 is the effective width of the strip waveguide. Here x and y are the longitudinal and tangential coordinates in the plate of the strip waveguide structure, respectively. Each reflector has width 2ω and is described by the phase delay kx_m. Then $U(p)$ can be derived as:

$$U(p) = \sum_{m=1}^{M} u_0(p) r t^{m-1} \exp(-\mathrm{i}kpx_m)\,, \tag{2}$$

where $k = 2\pi N/\lambda$, N is the effective refractive index of guided optical wave, r and t are amplitudes of the reflection and transmission coefficients, respectively, p is the sine of the angle of observation (measured with respect to the reflection axis – the direction corresponding to the optical beam reflected from the single reflector) and $u_0(p)$ is the angular spectrum radiated by the single reflector, given by:

$$u_0(p) = C \int_{-\omega}^{\omega} \exp\left(-\mathrm{i}kpx - (x/\omega_0)^2\right) \mathrm{d}x\,, \tag{3}$$

where C is the normalizing constant. Let us regard $\omega/\omega_0 \gg 1$, then we have:

$$u_0(p) = C(\pi)^{1/2} \exp\left(-(k\omega p/2)^2\right)\,, \tag{4}$$

$$u(p) = (\pi)^{1/2} \exp\left(-(k\omega p/2)^2\right) r \times \left(1 - t^{(M-1)} \exp(-\mathrm{i}kpdM)\right) \Big/ \left(1 - t\exp(-\mathrm{i}kpd)\right)\,, \tag{5}$$

The intensity of radiated field (radiated spectrum) has the form:

$$I(p) = |u(p)|^2 = C^2\pi \exp\left(-(kwp)^2/2\right) \times \left[\left(1 - t^{M-1}\right)^2 + 4t^{M-1}\sin^2(kd(1-p)(M-1)/2) \Big/ \left((1-t)^2 + 4t\sin^2(kd(1-p)/2)\right)\right]. \tag{6}$$

The radiated spectrum of the BE is shown in Fig. 2. It is similar to the spectrum of the "Echelon of Michelson" [10]. Equation (6) contains two cofactors. The first cofactor describes the angular spectrum of the light source formed by partial reflection of the confined guided TM mode. The last cofactor describes a line spectrum of periodic structure. The peak position corresponds to the case when $kd(1-p)/2 = \pi m_\lambda$. Thus, we have:

$$p = (\lambda_m - \lambda)/\lambda_m \,, \quad (7)$$

$$\lambda_m = dN/m_\lambda \,, \quad (8)$$

where m_λ is the integer order of interference. One can see that only those spectrum lines survive that are located near the reflector axis ($p = 0$). Thus the BE forms the expanded and highly collimated optical beam (see Fig. 2) that tilts with the optical wavelength according to (7). The second BE can be studied by the reverse in the direction of light propagation. It efficiently matches only that part of the incident optical beam that has the direction of propagation in accordance with the filtering condition of (7) to the strip optical waveguide. The work of the AO tunable filter (see Fig. 1) can be stated as follows. Two optical beam expanders are constructed in such a manner that their reflector axes are tilted at an angle θ, corresponding the double Bragg angle (θ_B) at the SAW center frequency of the AO Bragg sell. It has to be larger than the optical spread of the singly reflected beam ($\theta > 0.05$) to suppress the throughout spurious signal. The AO Bragg sell tilts the filtered optical beam radiated from the first BE and directs part of it (that satisfies the Bragg condition) to the second BE. The last BE can transmit only that part of beam light spectrum that satisfies the filtering condition of (7) at every desired optical wavelength. As the direction of propagation of the diffracted optical beam strongly depends on the optical and acoustic wavelength, the device drops different optical wavelength at different SAW frequencies.

It is possible to suppose that throughout device efficiency $I(\lambda)$ has to be proportional the convolution of the radiated spectrum of the first BE with the spectrum of the second BE, taking into account the shift of spectrum by the angle θ minus $2\theta_B$ (the angle change produced by the AO sell). For the case of isotropic diffraction (without change of the mode) we have [5]:

$$I(\lambda) = \int I(p) I(2\theta_B - \theta - p)\,\mathrm{d}p \,, \quad (9)$$

where $\theta_B = \arcsin(\lambda/(2\Lambda N))$ is the Bragg angle, Λ is the wavelength of SAW and θ is the angle that determines the reciprocal orientations of the two BE. One must mention that AOTF has multiple optical passbands near λ_m that correspond to different orders of the interference m_λ (8). For example, if $d = 7\,\mu m$, $N = 2.2$ then $\lambda = 1.54\,\mu m$ for $m_\lambda = 10$, $\lambda = 1.4\,\mu m$ for $m_\lambda = 11$, etc. We will discuss below the results for the case of the single transmission window near $1.54\,\mu m$ that corresponds to $m_\lambda = 10$. Figure 3 shows an example of the simulated throughout efficiency of the acousto-optic tunable filter on lithium niobate having a working length of 0.7 cm and a switching time between channels of only $2\,\mu s$. It is clear that by changing the SAW wavelength Λ, the device provides selective filtering of optical radiation within the tunable range $\Delta\lambda = 40\,nm$ at a $-3\,dB$ level. Both BEs contain 1000 reflectors with reflection coefficients 0.002. It can be shown [10] that a value for the reflection coefficients can be provided for a thin strip of $0.15\,\mu m$ width, which is embedded in the waveguide structure, when the refractive index of the strip differs from that of the waveguide by 0.04. For the lithium niobate case, such a strip can be manufactured by proton exchange (PE) technology, which provides a refractive index change of up to 0.12. For a waveguide based on chalcogenide glass, the reflectors can be developed by electron beam direct writing techniques, which provide a refractive index change up to 0.05 depending on the dose. Other technologies developed for microelectronics and other materials like AlGaAs are also available for the development of high efficient BE and are based on AOTF. It must be mentioned that the position of every reflector has to be manufactured with an accuracy of about $0.1\,\mu m$ to provide constructive interference for every reflected sub-beam of the device.

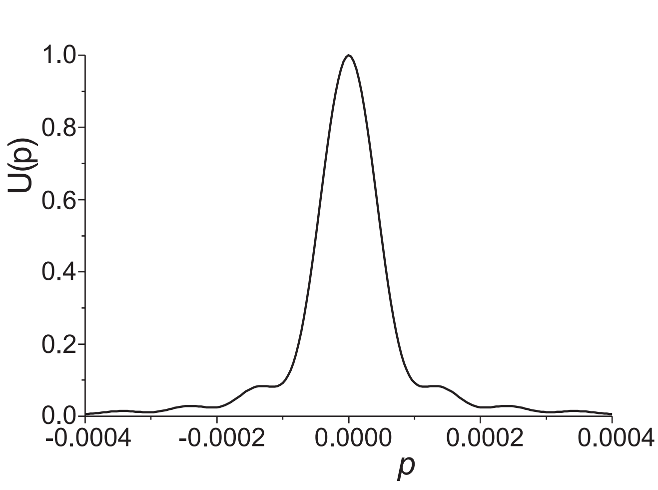

FIGURE 2 Radiated spectrum of the beam expander at $\lambda = 1.54\,\mu m$. The total aperture of the expanded beam is 0.7 cm

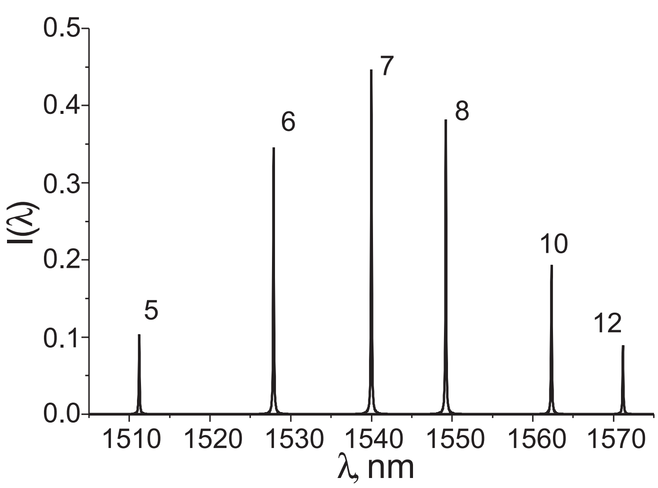

FIGURE 3 The tunable filter response at different SAW wavelengths: 5, $\Lambda = 5\,\mu m$; 6, $\Lambda = 6\,\mu m$; 7, $\Lambda = 7\,\mu m$; 8, $\Lambda = 8\,\mu m$; 10, $\Lambda = 10\,\mu m$; 12, $\Lambda = 12\,\mu m$

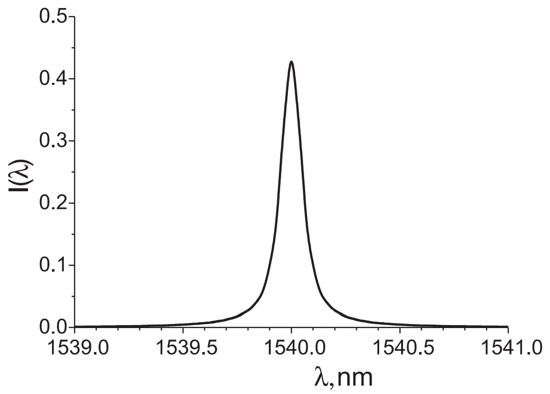

FIGURE 4 The tunable filter response in the vicinity of the optical bandpass. $L = 0.7$ cm

It can be shown [5] that for a given type of AOTF, the optical linewidth is described by the expression:

$$\delta\lambda = A\lambda^2/NL\,, \tag{10}$$

By comparing (1) and (10) it is evident that the tunable filter offered has an optical linewidth approximately $N/\Delta N$ times narrower than a standard collinear acousto-optic filter of equal size. For the lithium niobate case, it provides a narrowing of the optical linewidth of more than 20 times. This conclusion illustrates the tunable filter response that is shown in Fig. 4. It is clear that -3 dB optical linewidth is less than 0.1 nm (about 12 GHz), which for a 40 nm tuning range corresponds to 400 tuned optical wavelength channels. The total insertion losses of the device are estimated to be around 6–9 dB and strongly depend on manufacturing capabilities to minimize the waveguide propagation losses as well the losses in the fiber to strip waveguide coupling.

4 Conclusion

The concept of a novel type of acousto-optic tunable filter is presented, which simultaneously has a minimum size (working area about $1 \times 1\ \text{cm}^2$) and narrow optical linewidth (about 0.1 nm). It is polarization sensitive and intended for use with an external polarization controller that transforms an arbitrary polarization from the incoming fiber to the fundamental TM mode. The device can be developed by electron beam direct writing technology in any material suitable for development of perfect waveguide structures and efficient SAW excitation ($LiNbO_3$, $ZnO/SiO_x/Si$, ZnO/GaAlAs, etc.). The offered acousto-optic tunable filter can be utilized for the designing of wavelength-division multiplexing systems for fiber-optic networks, and also for the creation of small-sized tunable spectrometers for optical radiation, for example, in sensors of gases, liquids and solids. It can have a monomode fiber input and output and can be manufactured by modification of known technologies developed for the creation of integrated optics and microelectronic devices.

ACKNOWLEDGEMENTS The author thanks Prof. M.N. Armenise and Prof. V. Passaro from the Politecnico di Bari, Italy, as well as Dr. E. Kolosovsky from the Institute of Semiconductor Physics, Novosibirsk, Russia for the fruitful and helpful discussions concerning the proposed AOTF.

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