Fiber-Optic Switch-Multiplexer based on Acousto-Optic Modulators

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Abstract

A new acousto-optic switch-multiplexer for fiber-optic communication systems is developed and investigated. The device is based on new acousto-optic effect, which consists in high-effective multi-beam Bragg diffraction, which enables [1 x N] acousto-optic switching and multiplexing. As compared to other similar devices, the acousto-optic switch-multiplexer is capable of input optical signal transmitting not only to any one of output channels, but also to any group of channels simultaneously. A laboratory prototype of 20-channels switch-multiplexer for single mode fiber-optic communication link for 1.55 µm wavelength is constructed and tested.

1. Introduction

Nowadays the fast industrial growth of fiber-optic communication systems needs for improvement in optical switching tools. Recently developed industrial optical switches are usually based on the electro-optics or micro-electro-mechanics (MEMS). At the same time it is well known that with this concern the acousto-optics (AO) can offer several essential advantages, like the enhanced number of output channels, the faster time response, the absence of mechanically moving parts, the decrease of driving voltage, the increase of optical damage threshold and moderate values of insertion losses and cross-talks.

This work is devoted to the research and development of acousto-optic switch-multiplexer (AOSM) for [1 x N] fiber-optic channel switching with facility of input optical signal transmitting not only to any one output channel, but also to any group of channels simultaneously, up to all of them together.

The aim of the work is to create an experimental AOSM, investigate its utmost characteristics and to compare its potential parameters with similar ones for existing types of optical switches.

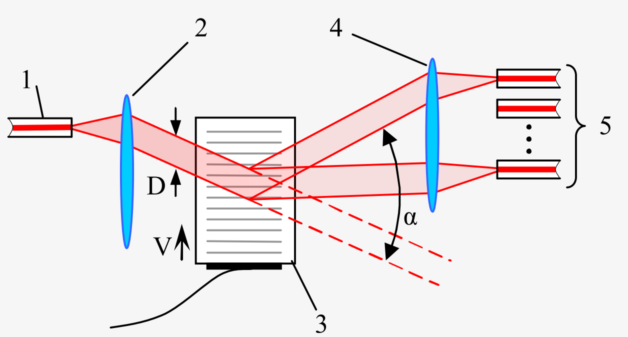

Fig. 1. Principal scheme of AO fiber-optic switch-multiplexer.

The operating principle of AOSM is shown on Fig. 1 [1]. Initial light beam, emitted by the input fiber 1 is collimated by the lens 2 on the input surface of the AO modulator 3. The aperture of the beam is denoted by D. An ultrasonic grating diffracts the initial beam by the angle, proportional to ultrasonic frequency: $\alpha = f\lambda/V$, λ being the light wavelength, V being sound velocity. Lens 4 focuses the diffracted beams onto the matrix of output fibers 5. The maximum number of fibers along one dimension is expressed as follows: $N_{1D} = \Delta f \tau = \Delta f\, D/V$, τ being the time needed by the ultrasonic wave front to pass the light aperture, i.e. the switching time, Δf being the AOSM frequency bandwidth.

2. Multi-beam Bragg Acousto-optic Diffraction

High-effective AOSM design principle is based on the new effect – multi-beam Bragg AO diffraction, which lies in high-effective (up to 100%) input beam splitting into several beams of equal powers [2-4]. Before cited works it was supposed that such splitting is fundamentally limited to low efficiency, which is illustrated by the Fig. 2. Here AO driving signal $U(t)$ is a sum of several independent frequency components with considerable powers. In this case the diffraction light field consist not only of the main (operating) beams K_d, but also includes numerous additional intermodulation beams K_{id} in the vicinity of main beams, as well as intermodulation beams K_{i0} in the vicinity of initial beam K_0. All these spurious beams accumulate a significant part of the input light power, that imposes restrictions of the diffraction efficiency maximum and the cross-talk ratio.

The new AO effect will appear when driving signal form is close to frequency-modulated one [1], i.e. when input frequencies are equidistant the particular amplitudes A_n and phases φ_n might be chosen to minimize the amplitude modulation of the aggregate signal:

$$U(t) = a(t)\exp(j\omega t), \qquad a(t) = \sum_{n=-\infty}^{\infty} A_n \exp(jn\Omega t + j\varphi_n), \qquad |a(t)| \approx const \tag{1}$$

Here ω is the central input frequency, Ω is the step between input frequencies, $a(t)$ denotes the modulation function. Under these conditions the inherent intermodulation effects are eliminated, and certain combinations of amplitudes and phases have to realize the input beam splitting into prescribed number of equal-intensity beams without spurious beams and with total efficiency close to 100%. The oscillograms on Fig. 3 show angular light power spectrums on the AO modulator output in case when the driving signal consist of five sine signals with frequencies from 35 MHz to 43 MHz with 2 MHz step. The X axis represents the angle, the Y axis – the light intensity. Fig. 3a shows the case without specific phasing between signal components, and it could be seen that diffraction field has at least seven beams of rather different intensities. On the contrary, Fig. 3b shows the diffraction field in case of correct amplitude-phase inter-signal relations, which makes the signal form close to frequency-modulated one. There are exactly five beams, they have equal powers and total diffraction efficiency is close to 100%.

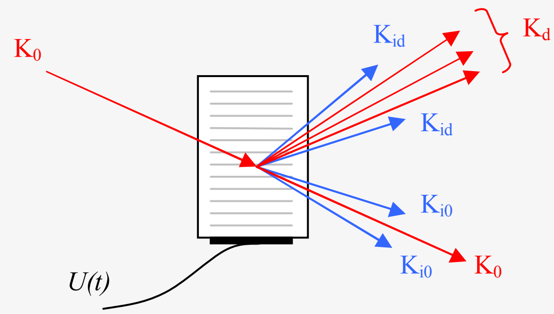

Fig. 2. Main (K_d) and spurious (K_i) diffraction orders under multi-frequency AO interaction.

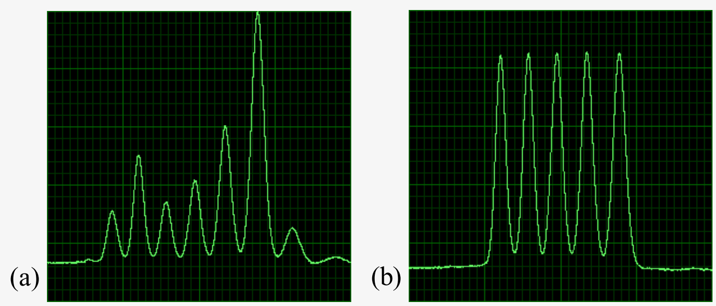

Fig. 3. Experimental diffracted light power angular spectrums: (a) – without any phasing, (b) – with correct inter signal phasing.

3. 2D Acousto-optic Switch-Multiplexer

The described effect of high-effective AO beam splitting leads to developing of fiber-optic channel multiplexer – a piece of apparatus for controllable transmitting of one input optical signal into multiple output channels. It should be pointed out that in contrast to passive multiplexers, AOSM performs controllable switching, i.e. the number and combination of output channels that receive input signal can be rapidly changed.

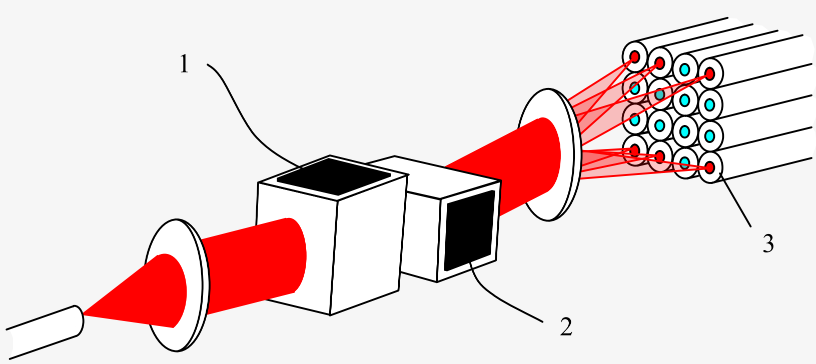

Fig. 4. Scheme of the 2D AO fiber-optic channel multiplexer

The scheme of the developed AOSM is presented on Fig. 4. Its peculiarity lies in using two orthogonally oriented AO modulators 1 and 2. This design yields to ability of two-dimensional output use (matrix of output fiber channels 3) with enhanced total number of channels $N_{2D} = N_{1D}^2$.

The most important parameters of switches under consideration are the number of channels and the front-end transmission losses (which depends on the AO diffraction efficiency limitations, optical scattering, misalignments, etc.), neighbor channels cross-talk and the operating speed (switching time). These characteristics obviously should be considered on the basis of reasonable compromises.

Fig. 5 shows theoretical dependence of the cross-talk between adjacent fibers (P/P_0) versus relative distance between the neighbor fibers cores L/d , where L is the distance between neighbor fiber axes in the matrix and d is the fiber core diameter. The beam is considered to have Gaussian angular distribution (curve G). The calculation does not consider the effects, related to light scattering by the fiber edges, lens and AO modulators surfaces. The relationship between the cross-talk, number of channels and switching time can be expressed as follows:

$$N_{2D} = \left(\Delta f \tau \cdot d/L\right)^2; \quad P/P_0 \sim \exp\left[-\left(L/d\right)^2\right] \qquad (2)$$

Fig. 6 shows the parameters, calculated according to (2) for light wavelength 1.55 μm and AO modulator bandwidth 16 MHz. It could be seen that one hundred of channels can be operated with switching time less than 10 μs, the relative distance between adjacent fibers L/d not being too small (about 8).

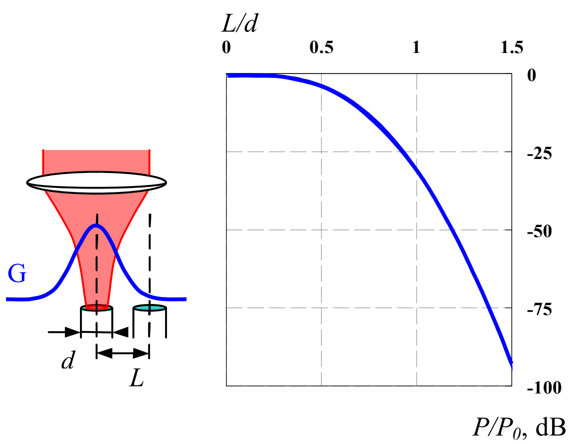

Fig. 5. Calculated cross-talk between adjacent single-mode fibers in the output matrix versus the distance between them

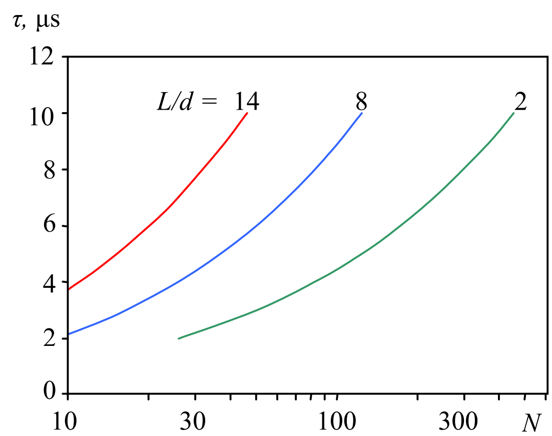

Fig. 6. Calculated switching time versus number of channels for different distances between adjacent fibers

A 20 channel experimental prototype of AOSM was constructed in accordance with the above predescribed design. Its picture is shown on Fig. 7. The output matrix was composed of single-mode fibers for 1.55 μm light wavelength. AO modulators were made of a single crystal paratellurite TeO_2. In accordance with theoretical estimations the measured parameters have been as following: switching time 5 μs, cross-talk -38 dB, insertion loss 4 dB, each modulator driving power 0.8 W.

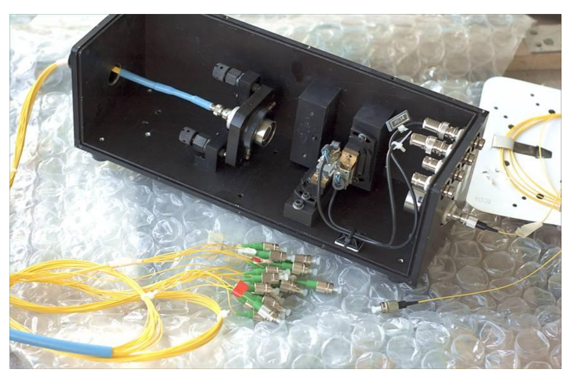

Fig. 7. Laboratory prototype of the 2D AOSM

The utmost parameters of the developed AOSM are presented in Table 1 in comparison with existing industrial fiber-optic switches based on MEMS and electro-optics. The analysis shows that AOSM has a remarkably enhanced

Table 1. Switches copmarison. Red – remarkable values, blue – drawbacks.

	MEMS	Electro-optics	AO
Number of channels	4 – 8	2	100 – 400
Switching time	10 – 20 ms	300 ns	3 – 6 µs
Insertion loss	1.5 – 2.5 dB	0.5 – 1 dB	3 – 4 dB
Cross-talk	50 dB	20 – 25 dB	30 – 40 dB
Optical power handling	300 – 400 mW	up to 500 mW	Not limited
Durability	10^6 cycles	Not limited	Not limited
Multiplexing capability	No	Yes	Yes

number of output channels, a moderate operating speed, and satisfactory cross-talk. Besides, it doesn't contain moving parts (which increases its durability) and can operate with high optical powers.

4. Conclusion

1. A method is developed for high-effective multi-channel controllable fiber-optic switch-multiplexer design based on multi-beam Bragg AO diffraction. It is shown that [1 x 100] switch-multiplexer can be constructed having switching time less than 10 µs.

2. An experimental prototype of single-mode fiber-optic switch-multiplexer was created, and following parameters were measured: number of channels 20, switching time 5 µs, cross-talk 38 dB, insertion loss 4 dB, each AO modulator driving power 0.8 W.

3. The comparative analysis with other types of optical switches shows that proposed AO technology provides the remarkably enhanced number of channels, moderate operating speed and satisfactory level of cross-talk.

5. Acknowledgments

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6. References

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