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Advanced integrated, acousto-optical switches, add-drop multiplexers and WDM cross-connects in $LiNbO_3$

H. HERRMANN, A. MODLICH, TH. MÜLLER,
W. SOHLER, AND F. WEHRMANN

Universität–GH Paderborn, Angewandte Physik,
D-33095 Paderborn, Germany
Tel.: Germany-5251-60-2714
Fax.: Germany-5251-60-3422

Abstract: A 4×4 WDM cross-connect consisting of five 2×2 acousto-optical switches has been realized with 10.1 dB insertion loss and 13.2 dB worst case crosstalk. To improve the crosstalk properties a new design for add-drop multiplexers has been developed and dilated switches have been investigated.

Introduction

Integrated acousto-optical, wavelength selective switches and add-drop multiplexers in $LiNbO_3$ are attractive devices for WDM networks (e.g.[1]). They offer fast and broad tuning exceeding the wavelength range of Erbium-doped fiber amplifiers. Unique is their multiwavelength operation capability. Single-stage devices with two input and two output ports have been developed during the last years [2]. They can be used as add-drop multiplexers. Moreover, these devices are the basic building blocks of more complex optical cross-connects. For instance, compact 4×4 switching nodes of high flexibility can be realized by combining five 2×2 components. However, crosstalk figures of single devices are typically limited to the range of −15 to −20 dB which is insufficent for WDM networks. Therefore, improvements especially concerning crosstalk reduction are required.

In this contribution we summarize the current state of single stage devices and present for the first time experimental results of a 4×4 optical cross-connect consisting of five 2×2 switches. Furthermore, improved configurations with reduced crosstalk using a monolithically integrated, double-stage add-drop multiplexer and hybrid dilated switches are discussed.

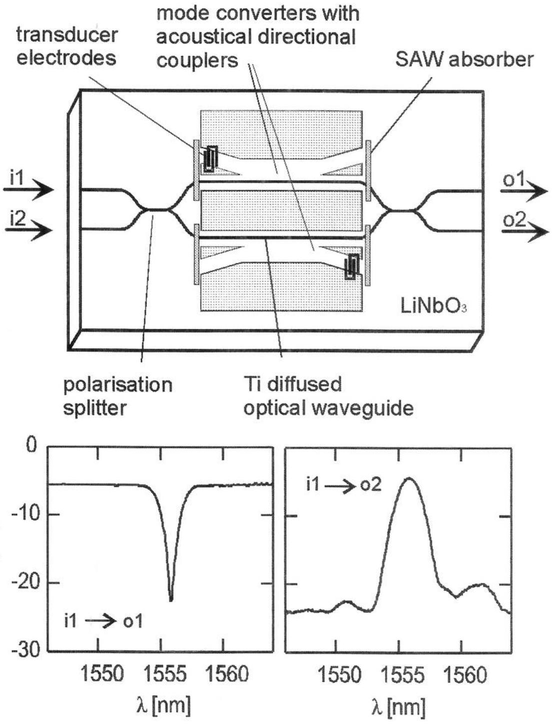

Fig. 1: Design and typical switching characterstics of a single stage 2×2 switch matrix / add-drop multiplexer.

Single stage acousto-optical 2×2 switch matrices

A schematic diagram of the 2×2 acousto-optical switches (AOTS) used for our experiments is shown in Fig. 1. Optical and acoustical waveguides have been fabricated by indiffusion of Ti into the $LiNbO_3$ substrate [2]. The switch structure consists of two acousto-optical TE-TM mode converters and two identical passive polarisation splitters/combiners. The light entering input port i1 is divided into its TE and TM polarised parts by the first polarisation splitter. The second splitter acts as a combiner. The optical power is routed to output port o1 ("bar state") if no mode conversion is performed. Via phase-matched acousto-optical interaction between a surface acoustic wave (SAW) and the optical fields a polarisation conversion (TE→TM or vice versa) can be induced. SAWs are excited by applying rf signals to the transducer electrodes. If the state of polarisation (SOP) changes, the light is routed to output port o2 ("cross state"). The mode conversion is wavelength selective (halfwidth ≈ 2 nm); wavelength tuning is accomplished by varying the SAW frequency around 170 MHz. The SAWs in the mode converters propagate into opposite directions to achieve identical frequency shift for TE and TM components. This avoids beating effects which would disturb the performance of the switch seriously [3].

Crosstalk occurs due to nonideal polarisation splitters, mode conversion efficiencies of less than 100%, and sidelobes of the mode conversion characteristics. In Fig. 1 typical – but not the best one – switching characteristics are shown. The broadband amplified spontaneous emission (ASE) from an Erbium doped fiber amplifier (EDFA) has been coupled into port i1 and the transmitted signals at the output ports o1 and o2, respectively, have been measured using an optical spectrum analyser. Insertion losses are in the range of 3–5 dB. Typical sidelobe suppression of the bandpass characteristic (i1→o2) is about −15 dB to −20 dB. The extinction of the notch curve (i1→o1) is typically limited to about −15 dB to -20 dB, too.

2×2 switches form the basic building blocks of more complex optical cross-connects or they may be used as add-drop multiplexers e.g. in a WDM ring network. However, stringent demands concerning the crosstalk figures are required, which can hardly be achieved by these single-stage devices. Therefore, double-stage approaches have been investigated to improve the performance properties.

Improved add-drop multiplexers

A new approach of a double-stage multiplexer is shown in Fig. 2. Optical channels transmitting the device from input port I to output port O pass two special 2 × 2 matrices switched to the bar-state in series. To drop a single channel the first matrix is switched to the cross-state and the signal is fed to the drop output port D. In a similar way a signal can be added by launching it to add input port A and switching the second matrix to the cross-state. The matrices are realized by embedding the arms for both polarisations in the same acoustical waveguide. This avoids waveguide bendings but induces opposite frequency shifts for the converted add- and drop channels. Additional acousto-optical mode converters in the add- and drop arms are used to compensate this frequency shift.

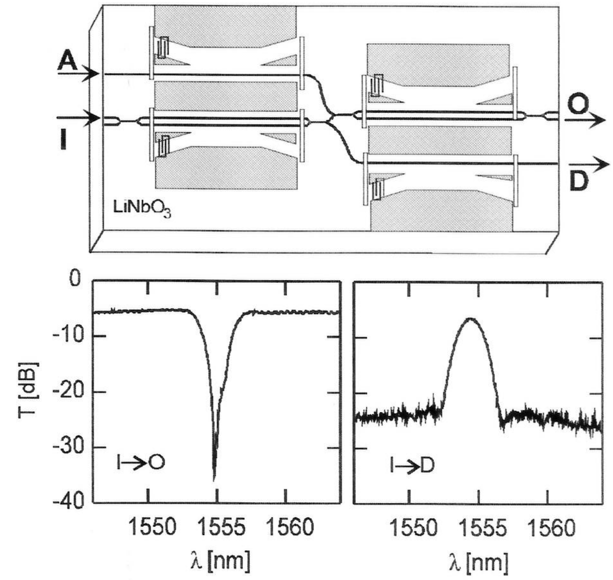

Fig. 2: Design and switching characteristics of the advanced integrated acousto-optical add-drop multiplexer.

The advantages of the new structure are obvious: Crosstalk due to incomplete dropping of a channel is reduced as residual parts of the drop signal which would be routed towards O are additionally suppressed in the second matrix. Moreover, there is a strong isolation of the D port from signals entering the A port, i.e. no crosstalk between add- and drop signals can be expected.

First integrated optical devices of this new circuit have been realized. As an example in Fig. 2 measured switching characteristics are shown. They demonstrate the drop-function of the device. Extinction of the notch curve (I→O) is larger than 30 dB. The bandpass characteristics (I→D) has a large baseline floor of about −18 dB due to imperfect polarisation splitters. Moreover, a pronounced polarisation dependence of the insertion losses as well as of the crosstalk characteristics has been observed. The first devices are still not ideal. However, the basic advantages of the design could be verified. With a further improvement of the single elements forming the circuit a significant improvement of the overall device performance can be expected.

4×4 WDM cross-connect

To investigate performance of acousto-optical devices in more complex WDM-structures a reconfigurable nonblocking 4×4 optical cross-connect has been realized using five 2×2 acousto-optical single stage switches (Fig. 3). The node architecture allows – as conventional space switches – a set of four information channels (incoming at the four input ports i1,...,i4, each being transmitted at the same wavelength λ) to be connected to the four output ports o1,...,o4 in arbitrary order (each output transmits one input signal). Moreover, due to the multi-wavelength operation of the switches the node is able to route several wavelengths λ_i simultaneously and independently. In this way, one achieves the same functionality as for example the much more complicated cross-connect realized in the EU-RACE project "MWTN"[4].

In particular, it is possible to demultiplex a WDM signal being present at one of the input ports. Assuming, for example, the cross-connect should route four incoming WDM-channels (λ_1 = 1548 nm, λ_2 = 1552 nm, λ_3 = 1556 nm and λ_4 = 1560 nm) present at input i2 to the output ports o1, o2, o3 and o4, respectively, the individual 2×2 switches must be set into the cross-state for the various wavelengths as indicated in Fig. 3. By using again the ASE of an EDFA as light source coupled into input i2 the transmitted spectra at the output ports have been measured (Fig. 3). The worst case crosstalk for this particular case is -16 dB, resulting from polarisation splitter leakage in switch 5 (only 14.5 dB splitting ratio for TE polarised light). Routing the wavelengths λ_i to output ports o_i in ways different to that shown in Fig. 3 results in different crosstalk figures with -12.8 dB worst case caused by interchannel interaction due to strong sidelobes of one of the switches. This worst case figure is of course limited by the performance of the worst switch in the node. Improving the crosstalk performance of the 2×2 switches is therefore necessary to achieve crosstalk figures below -20 dB for the complete node. The insertion loss of the complete node ranges from 8.7 to 10.1 dB for unpolarised ASE noise.

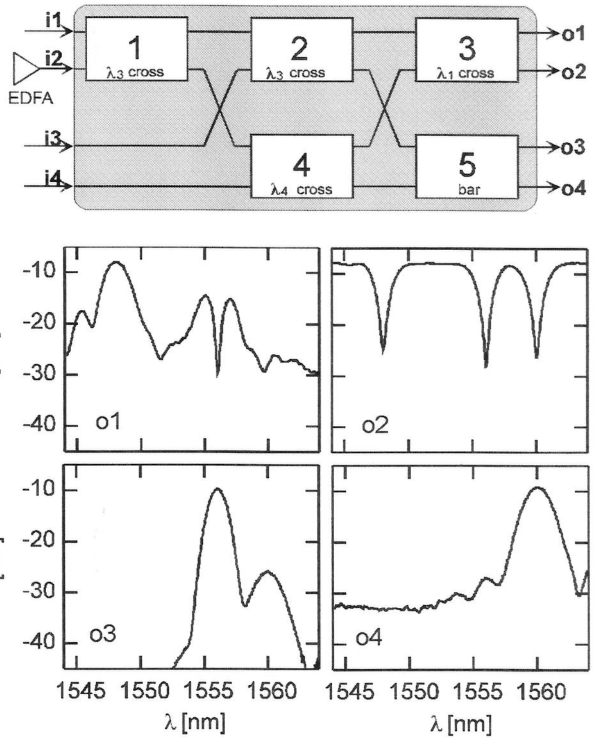

Fig. 3: Optical 4×4 cross-connect experiment.

Hybrid dilated switches

One possibility to improve the crosstalk figures of a 2×2 switch is the dilated switch consisting of four 2×2 switches being switched to cross or bar state jointly [5]. Fig. 4 shows the dilated switch architecture and the transmission spectra when unpolarised ASE noise is launched into input port i1 and all switches are set to cross state for 1552 and 1556 nm. The worst case extinction ratio of the notch curve is now -27.1 dB (intrachannel crosstalk) when two 4 nm spaced wavelengths are switched simultaneously. The interchannel crosstalk at 4 nm spacing is better than -30.6 dB. However, cascading the devices results in narrower pass- and stopbands which makes the dilated switches more sensitive to wavelength drifts. The insertion loss increases which is a clear

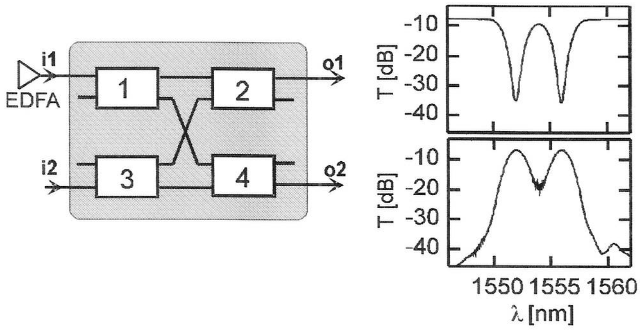

Fig. 4: Dilated switch experiment.

disadvantage as well but the crosstalk figures are strongly improved.

Towards monolithically integrated dilated switches

A further severe disadvantage of the dilated switch discussed above is that it consists of four individual devices connected by fibers. Therefore, it should be the aim to integrate the four 2×2-switches on the same substrate without any further fiber connections. The length of a single 2×2-switch, however, is already about 60 mm. A fully integrated version of the dilated switch would require at least twice this length. As, up to now, only 4"-wafers are available and the technology for fabricating circuits of large dimensions is extremely difficult, a fully integrated version of the dilated switches is far beyond the current possibilities.

A first approach towards a larger integration density, however, is to realize a dilated switch using two of the improved add-drop multiplexers discussed above. In Fig. 5 this is schematically shown. By connecting the drop output of the first multiplexer with the add input of the second one and vice versa, a dilated switch can be realized. Furthermore, it should be possible to fabricate both multiplexers on the same substrate. In this case only two additional fiber connections are necessary.

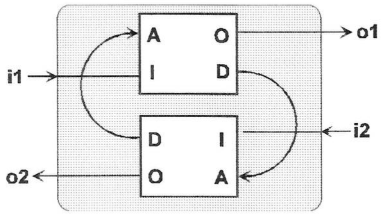

Fig. 5: Dilated switch composed of two advanced add-drop multiplexers.

Conclusions

Integrated acousto-optical devices in $LiNbO_3$ have been studied as basic building blocks for WDM cross-connects. Using five 2×2 acousto-optical switches a 4×4 cross-connect has been investigated. Insertion loss of the node is 10.1 dB and the worst case crosstalk 13.2 dB.

To improve the crosstalk properties a dilated 2×2 switch consisting of four single stage 2×2 switches has been investigated. It has been demonstrated that the crosstalk could be reduced by more than 10 dB in this configuration. Moreover, a monolithically integrated double-stage add-drop multiplexer has been developed. Although its performance properties are still not ideal, a reduction of the crosstalk could be demonstrated. Additionally, these new add-drop multiplexers can be used to realize dilated 2×2 switches on a single substrate with only two additional fiber connections.

Acknowledgement

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