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Double-Stage, Integrated, Acousto-Optical Add-Drop Multiplexers with Improved Crosstalk Performance

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Abstract: A new type of integrated acousto-optical add-drop multiplexer in $LiNbO_3$ has been developed combining four acousto-optical mode converters and four polarization splitters. The pigtailed device yields high extinction (> 25 dB) and neglectable crosstalk between add- and drop signals.

Introduction

Future wavelength division multiplexing (WDM) systems require add-drop multiplexers of high quality. These devices should be tunable to allow a flexible routing of wavelength channels. It has been shown that integrated acousto-optical circuits [1] in $LiNbO_3$ can meet this requirement as they offer a large tuning range and, moreover, simultaneous multi-wavelength operation capabilities.

Tunable 2×2-switches/add-drop multiplexers [2] have been developed with excellent performance especially concerning insertion loss, polarization dependence and tuning range. However, crosstalk is still a serious problem. It arises due to non-ideal performance of the individual components of the circuit. Typical crosstalk figures are about 15 dB especially for the extinction of the dropped channels and for the direct coupling of the added signal to the dropped output. The latter is a very serious problem if the power level of the add signal is orders of magnitude higher than that of the dropped channels.

To reduce the crosstalk *dilated* 2×2 switches can be realized by combining four conventional 2 × 2 switches [3][4]. A full integration on a single chip is not yet possible as the circuit exceeds the dimension of available wafers. However, as add drop multiplexers do not need the full functionalty of a 2×2 switch improved multiplexers can be fabricated taken partially advantage of the principle of dilation.

Circuit design and principle of operation

A schematical diagram of the new multiplexer is shown in Fig. 1. The circuit consists of two switches in series and two frequency shifters. Each switch itself is formed by two polarization splitters and an acousto-optical mode converter. The input is split into its polarization components by the first polarization splitter and routed to separate optical waveguides embedded in a common acoustical waveguide. This forms one branch of an acoustical directional coupler. A surface acoustic wave (SAW) excited in the other branch by an RF-signal applied to the interdigital transducer electrodes couples to the acoustical guide with the embedded optical channels and induces

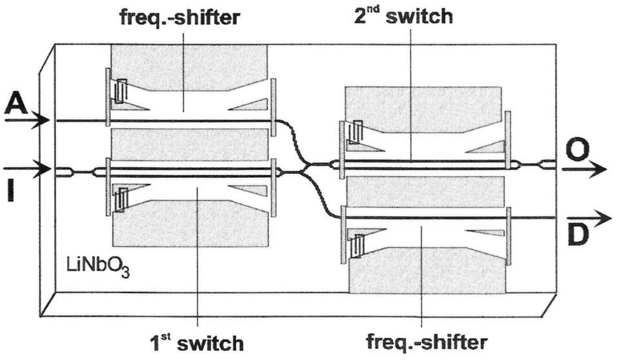

Fig. 1: New design of the integrated acousto-optical add-drop multiplexer.

a polarization conversion. This process requires phase-matching, i.e. for efficient conversion the wave number of the SAW must compensate the difference of the wave numbers of the TE- and TM-polarized optical waveguide modes. Therefore, the conversion process is wavelength selective and can be tuned by varying the SAW frequency. After passing the mode converter the optical waves are recombined in the second polarization splitter. It routes the converted waves to the cross-state and the unconverted waves to the bar-state output of the switch.

In the first switch of the multiplexer the drop function is performed, i.e. the selected channels are converted and routed towards the drop output D. The residual channels from the transmission line are fed to the input polarization splitter of the second switch. In this switch the add signals (from input A) are added and routed to the transmission line output O. Additionally, the residual part of the drop signal which has not been coupled to the drop port due to imperfections of the first switch is converted in the second switch and routed to the unterminated cross-state, i.e. the device acts as double-stage notch filter for the transmission path from I to O. Moreover, add- and drop functions are locally separated, i.e. spatially dilated, resulting in neglectable crosstalk between the add and drop ports.

Due the acousto-optical conversion process the frequency of the converted optical waves are shifted by the SAW frequency. The direction of the shift depends on the conversion direction (TE→TM or TM→TE) and on the propagation direction of the SAW. As both polarization components in the switches are converted by the same SAW, the converted waves obtain an opposite frequency shift. To compensate this shift a further mode conversion is performed for the add- and drop signals in the two frequency shifters.

Fabrication

For most of the fabrication steps Ti-indiffusion technology in X-cut, Y-propagating $LiNbO_3$ is used. First, the acoustical guiding structures are performed by indiffusion of 160 nm thick titanium for 24 h at 1060 ^{o}C into the cladding regions. In a further Ti-diffusion process optical waveguides and polarization splitters are fabricated by an indiffusion of about 100 nm thick Ti-stripes.

7 μm wide optical guides are used to achieve low loss (typical < 0.2 dB/cm) single mode guiding in both polarizations. The splitters consist of passive zero gap directional coupler structures with a 340 μm long central segment of 14 μm width. The splitting ratios are typically better than 20 dB and the excess losses below 0.7 dB [5].

Interdigital aluminium transducer electrodes consisting of 24 finger pairs are deposited on top of the substrate and drops of UV-curing glue acting as acoustical absorbers to terminate the interaction lengths. The spectral conversion characteristics of the mode converters show typically sidelobes about 15 dB below the main transmission peak. Ideally, these sidelobes should be below -20 dB for the weighted coupling process realized by using 19 mm long acoustical directional couplers [6]. This discrepancy is due to residual inhomogeneities of the optical waveguide structure. Moreover, we found that for a fixed optical wavelength the SAW frequencies for phase-matched conversion in the two switches differ sligthly. To compensate this difference the integrated optical chip is mounted on a copper holder which allows a separate temperature stabilization of the two switches. Optimum performance is achieved at a temperature difference of about 3.2 ^{o}C.

Before pigtailing the 72.3 mm long device with standard single mode fibers quarter-wave layers of Y_2O_3 acting as AR-coating are evaporated on the end-faces of the waveguide.

Device performance

For the characterisation of the fiber-pigtailed and packaged device the broadband amplified spontaneous emission (ASE) from a erbium doped fiber amplifier has been used as light source and the transmitted spectra have been measured using an optical spectrum analyzer with 0.1 nm resolution bandwidth. In Fig. 2

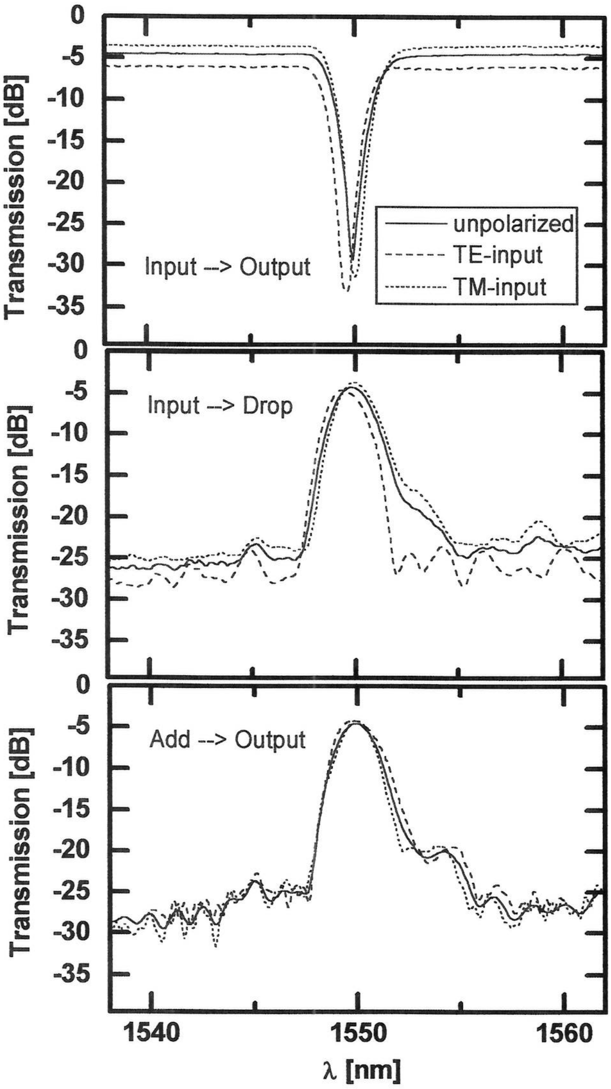

Fig. 2: Measured transmission spectra for various input and output combinations.

experimental results are shown for various input and output combinations. In each diagram the transmission versus wavelength is plotted for unpolarized input light as well as for TE and TM polarized input. The mode converters have been driven by RF-signals at $f = 174.680$ MHz to operate the device at $\lambda = 1550$ nm.

The upper diagram of Fig. 2 shows the spectral notch characteristics for the transmission from port I to port O. For unpolarized input the insertion loss is about 4.5 dB, for TM and TE polarized input 3.6 dB and 5.9 dB, respectively. That means, that there is a residual polarization dependence of the insertion losses of 2.3 dB. Due to the double-stage design the extinction for TE and TM polarized input is 27.2 dB and 27.6 dB, respectively. As there is a small wavelength shift between the transmission minima, the extinction for unpolarized input is only 25 dB. However, it is about 10 dB better than that obtained with typical single-stage multiplexers [2]!

The other two diagrams of Fig. 2 demonstrate the add- and drop functions of the device. The 3-dB spectral width of the transmission curves is about 2 nm. Insertion losses are below 5 dB and the polarization dependence of the losses is smaller than for the I→O path: For the drop and add functions a polarization dependence of 1.2 dB and 0.1 dB, respectively, have been measured. As for the add- and drop functions only a single-stage filtering is performed the sidelobe suppression is still not ideal. For instance, the suppression of signals being 4 nm separated from the transmission peak is 16 dB (worst case).

The crosstalk between added input and dropped output is neglectable. Within the dynamic range of our measurement setup of about 50 dB we could not observe any crosstalk.

The add signal at the output O and the drop signal at output D, respectively, have been investigated with a Fabry-Perot type spectrum analyzer with 1.9 GHz free spectral range to study the performance of the frequency shifters. For these measurements a narrow-band DFB-laser ($\lambda = 1545$ nm) has been used as light source. In Fig. 3 the corresponding measured spectra are shown for an input polarization which excites TE- and TM-modes with equal strength. Without operating the frequency shifter the orthogonal polarization components obtain opposite frequency shifts in the corresponding switch which can be seen in the diagrams as dotted lines. There occur two peaks of orthogonal polarization separated 350.8 MHz which is twice the acoustical frequency. The solid curves show the experimental results with operating frequency shifters. The compensation of the frequency shifts of the add signal is nearly ideal. In the drop signal, however, about 10 % of the light could

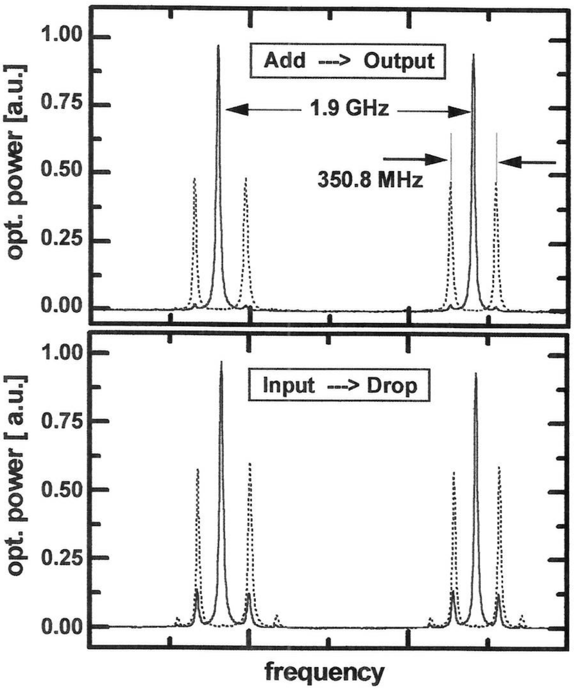

Fig. 3: Transmission spectra measured with a Fabry-Perot interferometer. The two curves in each diagram belong to measurements with (solid) and without (dotted) operating frequency shifters.

not be converted as the exact phase-match frequency does not exactly coincide due to inhomogeneities with that of the first switch.

Residual unshifted waves can interfere with the shifted wave resulting in an intensity modulation if the waves have same polarization components. This would occur at the drop output. Without operating the corresponding frequency shifter, however, the two waves (being about 350 MHz separated) have orthogonal polarizations and, hence, do not beat. Therefore, the device can be operated without the shifters if no mixing of the polarization components occurs behind the device. This would be true for the drop signal if the output is directly routed to a receiver without any polarizing elements inbetween. For the added signal, however, there should be no shift as on the transmission line components with polarization dependence can cause such a mixing.

The add-drop multiplexer has been investigated for wavelengths from 1530 nm to 1570 nm. No significant change of the performance has been observed. The RF drive powers for the converters of the two switches are 18.7 dBm and 17.0 dBm; for the shifters are 20.3 dBm and 25.4 dBm required. The high power requirement of one of the shifter is due to a partially destroyed transducer. A similar device (with slightly worse performance) requires only a drive power of 180 mW for all converters together.

Conclusions

A new type of integrated acousto-optical add-drop multiplexer in $LiNbO_3$ has been developed. With the double-stage configuration extinction ratios of more than 25 dB have been achieved and the crosstalk between add and drop signals is completely eliminated. These new devices are very promising candidates for applications in WDM networks. System experiments are planned within the EU ACTS project 'METON'.

Acknowledgement

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