Low-Loss Tunable Integrated Acoustooptical Wavelength Filter in $LiNbO_3$ with Strong Sidelobe Suppression

H. Herrmann, *Member, IEEE,* K. Schäfer, and Ch. Schmidt

***Abstract*— An integrated acoustooptical double-stage wavelength filter in $LiNbO_3$ has been developed using acoustooptical polarization converters and polarization splitters as basic components integrated on the same chip. Ti-indiffusion technology is used throughout to fabricate the device. The packaged and pigtailed filter has low insertion losses (4.1 dB fiber-to-fiber), low-polarization dependence (0.1 dB) and a strong sidelobe and baseline suppression (>30 dB). Its tuning range exceeds the gain bandwidth of erbium-doped fiber amplifiers around 1550 nm.**

***Index Terms*—Acoustooptical filters, integrated optics, tunable filters, wavelength division multiplexing, wavelength filters.**

I. INTRODUCTION

INTEGRATED acoustooptical circuits in $LiNbO_3$ are attractive devices for a variety of applications, in particular, in wavelength-division multiplexing (WDM) optical communication systems [1]. However, stringent specifications concerning insertion loss, crosstalk and polarization sensitivity are required for most of the applications. To meet such requirements tunable acoustooptical wavelength filters have been developed using a double-stage design [2]. The design of these filters, however, is complex; besides acoustooptical mode converters and polarization splitters additional TE- and TM-pass polarizers are used, fabricated by different technologies. Their performance is very sensitive to the fabrication conditions and aging effects can result in a degradation of the extinction ratio.

To overcome these drawbacks a double-stage acoustooptical tunable wavelength filter in $LiNbO_3$ without polarizers has been developed. The device consists of acoustooptical mode converters and polarization splitters, all fabricated by Ti-indiffusion. Therefore, the technology is strongly simplified in comparison with that described in [2]. Moreover, the design of the filter is tolerant to a nonideal performance of the individual components.

II. CIRCUIT DESIGN AND PRINCIPLE OF OPERATION

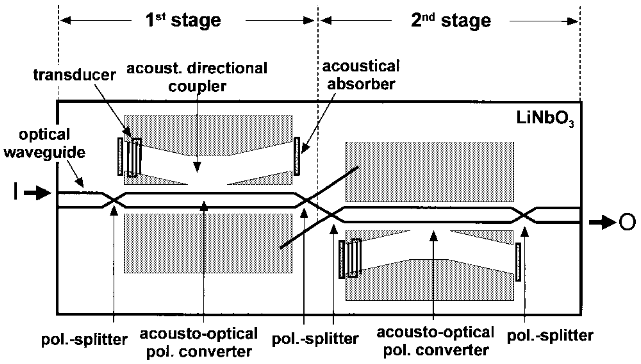

Fig. 1. Schematical diagram of the integrated acoustooptical wavelength filter.

A schematical diagram of the new design is shown in Fig. 1. It essentially consists of two single-stage wavelength filters in series. Each filter itself is formed by an acoustooptical polarization converter between two polarization splitters [3]. In both stages, the input is split by the first polarization splitter into TE- and TM polarized modes routed to different optical waveguides. Both are embedded in a common acoustical waveguide which forms one branch of an acoustical directional coupler. In the other branch, a surface acoustic wave (SAW) can be excited via an RF-signal applied to the interdigital transducer electrodes. The SAW is coupled to the adjacent acoustical guide and back again resulting in a weighted acoustooptical interaction [4]. This yields a wavelength dependent coupling between TE- and TM-polarized optical modes. For efficient conversion the phase-matching condition $|\beta_{\mathrm{TE}} - \beta_{\mathrm{TM}}| \approx |k_{ac}|$ must be fullfilled. β_{TE} and β_{TM} are the wave numbers of the TE- and TM-polarized waves, respectively, and k_{ac} is the wave number of the SAW. As $\Delta\beta = \beta_{\mathrm{TE}} - \beta_{\mathrm{TM}}$ is wavelength dependent, the acoustic wave number and, hence, the SAW frequency determines the wavelength of efficient conversion.

After passing the acoustooptical mode converter the signals are recombined by the second polarization splitter. As the state of polarization of the phase-matched waves has been changed, they are separated from the unconverted ones. The converted waves are routed to the input arm of the second stage whereas the unconverted ones are fed to a waveguide which is terminated on the substrate outside of the interaction area of the second stage.

The double-stage design offers the following advantages: First, the filter characteristic of the overall device is the product of the filter characteristics of the individual stages. This yields a strong suppression of sidelobes and a narrowing of the spectral filter response. Even if one stage has a nonideal performance, e.g., large sidelobes or bad splitting ratios of the polarization splitters, cascading with the other (better) stage still results in a good overall device performance.

Manuscript received June 23, 1997; revised October 7, 1997.

The authors are with the Angewandte Physik, Universität-GH Paderborn, D-33098 Paderborn, Germany.

Publisher Item Identifier S 1041-1135(98)00447-9.

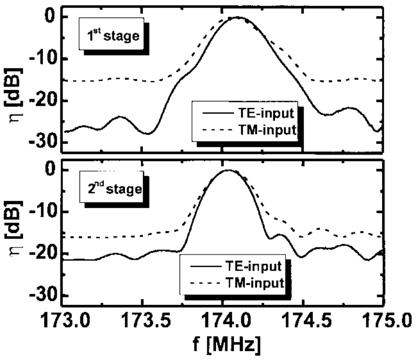

Fig. 2. Conversion efficiency η of the individual stages for TE and TM input polarization versus SAW frequency at fixed optical wavelength $\lambda = 1555$ nm.

Second, the double-stage design results in a compensation of the frequency shift accompanying any acoustooptical conversion by the frequency of the SAW. As the direction of the frequency shift (up- or down shift) depends on the input polarization (TE or TM) and on the propagation direction of the SAW relative to the propagation direction of the optical waves, the opposite shifts of both polarization components in the first stage are exactly compensated in the second stage.

III. Fabrication and Characterization

As substrate material X-cut LiNbO$_3$ with Y-propagation is used. Acoustical and optical waveguides are fabricated using Ti-indiffusion technology. In a first step the acoustical waveguides are defined by an in-diffusion (31 h at 1060 °C) of a 160-nm-thick Ti-layer into the cladding region of the acoustical guiding structures, which are 19.1-mm-long tapered acoustical directional couplers; details of the structure are given in [4].

Subsequently, the optical waveguide structure is fabricated again by Ti-indiffusion (13 h at 1060 °C). For single mode waveguides about 100-nm-thick 7-μm-wide stripes are indiffused. The attenuation of the optical waveguides has been measured to be about 0.3 and 0.1 dB/cm for TE and TM polarized waves, respectively.

The polarization splitters consist of passive directional couplers with zero gap. TE-polarized light is coupled to the cross-state, TM-polarized to the bar-state. Details of the structure are given in [2]. Splitting ratios have been determined to be better than 20 dB for both polarizations. Excess losses are typical about 0.5 dB.

In the next fabrication step, aluminum interdigital transducer electrodes consisting of 24 finger pairs are deposited to allow the excitation of SAW's. Drops of UV-curing glue acting as acoustical absorbers are used to terminate the acoustooptical interaction length.

To characterize the first stage alone, TE or TM polarized light from a DFB-laser diode ($\lambda = 1555$ nm) has been coupled into the waveguide adjacent to the output waveguide. The power transmitted through the port I waveguide as function of the SAW frequency gives the conversion characteristics of the first stage, if the SAW in the second stage is switched off. To characterize the second stage, the light is coupled into the waveguide adjacent to the input guide and the second stage is operated alone. In Fig. 2, results of these measurements are shown. The conversion curves of the first stage are broader than that of the second stage due to residual inhomogeneities of the optical waveguides. Furthermore, there is a slight separation of the transmission maxima for TE and TM in the first stage. Due to better splitting ratios of the polarization splitter for TE the baseline of the conversion curve is lower than that for TM input polarization.

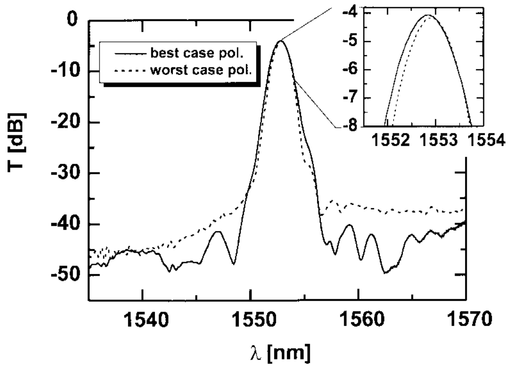

Fig. 3. Filter characteristics of the packaged and pigtailed wavelength filter for best and worst case input polarization using a broad-band spectrum at the input port I.

The frequency for maximum conversion is slightly different for the two stages indicating again a nonideal waveguide homogeneity. To operate both stages with the same SAW frequency to achieve a zero net frequency shift, the conversion curves have been aligned via temperature tuning.

Before pigtailing the 69.8-mm-long device with single mode fibers, the waveguide end-faces have been AR-coated using a quarter wave layer of Y$_2$O$_3$.

IV. Overall Device Performance

The fully packaged and pigtailed wavelength filter has been characterized using as broad-band light source the amplified spontaneous emission from an erbium-doped fiber amplifier (EDFA). The transmitted signals have been investigated with an optical spectrum analyzer of 0.1-nm resolution.

In Fig. 3, the transmission of the filter versus optical wavelength is shown. Two curves are drawn corresponding to an input polarization with minimum and maximum insertion loss at the peak transmission, respectively. The bandwidth (full-width at half-maximum) is 1.6 nm. There are no pronounced sidelobes in the filter characteristics and the baseline, i.e., the residual transmission at a wavelength far away from the filter peak, is more than 30 and 40 dB below the transmission maximum for the best and worst case input polarization, respectively. As can be seen in the inset of Fig. 3 the polarization dependence of the device is very small. The peaks at maximum transmission are separated by about 0.07 nm and the insertion loss difference is about 0.1 dB. The overall insertion (fiber-to-fiber) is less than 4.2 dB for the worst-case input polarization.

The tuning range exceeds the wavelength range available from the ASE of the amplifier. Even without readjusting the RF drive power of 100 mW for both stages together, the filter can be tuned from 1530 to 1570 nm without a significant degradation of the filter characteristic.

V. CONCLUSION

A new type of integrated acoustooptical filter has been developed. It is characterized by low insertion loss, small polarization dependence and strong sidelobe suppression. Moreover, the device technology is strongly simplified requiring only Ti-indiffusion for the fabrication of optical and acoustical waveguides and of integrated polarization splitters/combiners. Therefore, the new type of filter offers a great potential for future mass production. It will mainly be used in fiber-optical WDM communication systems; for instance, as channel selectors, for gain equalizing of fiber amplifiers using the unique property of simultaneous multiwavelength operation [5], [6] or as channel analyzer [7].

REFERENCES

[1] D. A. Smith, R. S. Chakravarthy, Z. Bao, J. E. Baran, J. L. Jackel, A. d'Alessandro, D. J. Fritz, S. H. Huang, X. Y. Zou, S. M. Hwang, A. E. Willner, and K. D. Li, "Evolution of the acousto-optic wavelength routing switch," *J. Lightwave Technol.*, vol. 14, pp. 1005–1019, 1996.

[2] F. Tian, Ch. Harizi, H. Herrmann, V. Reimann, R. Ricken, U. Rust, W. Sohler, F. Wehrmann, and S. Westenhöfer, "Polarization independent integrated optical, acoustically tunable double stage wavelength filter in $\mathrm{LiNbO_3}$," *J. Lightwave Technol.*, vol. 12, pp. 1192–1197, 1994.

[3] H. Herrmann, K. Schäfer, and W. Sohler, "Polarization independent, integrated optical acoustically tunable wavelength filters/switches with tapered acoustical directional coupler," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 1192–1194, 1994.

[4] H. Herrmann, U. Rust, and K. Schäfer, "Tapered acoustical directional couplers for integrated acousto-optical mode converters with weighted coupling," *J. Lightwave Technol.*, vol. 13, pp. 364–374, 1995.

[5] S. F. Su, R. Olshansky, G. Joyce, D. A. Smith, and J. E. Baran, "Gain equalization in multiwavelength lightwave systems using acoustooptic tunable filters," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 269–271, 1992.

[6] S. H. Huang, X. Y. Zou, A. E. Willner, Z. Bao, and D. A. Smith, "Experimental demonstration of active equalization and ASE suppression of three 2.5 Gbit/s WDM-network channels over 2500 km using AOTF as transmission filters," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 389–391, 1997.

[7] St. Schmid, S. Morasca, D. Scarano, and H. Herrmann, "High performance integrated acousto-optic channel analyzer," *Conf. Optical Fiber Communication (OFC '97)* OSA Tech. Dig. Ser. Washington, DC: Opt. Soc. Amer., 1997, vol. 6, pp. 7–8.