All-Fiber Acoustooptic Filter with Low-Polarization Sensitivity and No Frequency Shift

Seok Hyun Yun, D. J. Richardson, D. O. Culverhouse, and T. A. Birks

***Abstract*—An acoustooptic tunable filter based on an all-fiber null coupler, exhibiting low polarization sensitivity and zero net frequency shift, is demonstrated. The polarization dependence has been eliminated by simultaneously applying two acoustic waves that independently satisfy the phase-matching condition for the two eigenpolarization states. A simple double-pass arrangement is employed to exactly cancel the net frequency shift and to provide an enhanced spectral sidelobe suppression of better than -17 dB.**

***Index Terms*—Acoustooptic filter, optical fiber couplers, optical filter, tunable filter.**

ACOUSTOOPTIC tunable filters (AOTF's) with fast switching speeds and the ability to control several channels independently, offer great potential for wavelength selection, switching and routing in WDM transmission systems [1]. To date most research has been focused on integrated-optic $LiNbO_3$ waveguide devices in which acoustooptic (AO) coupling takes place between the TE and the TM polarization modes via a surface acoustic wave [2], [3]. However, since the technique is based on polarization mode conversion, complex polarization diversity configurations employing polarization splitters/combiners have been necessary to realize polarization-independent operation; a fundamental requirement for any practical device. Furthermore, the diversity approach can result in a number of further technical problems related to the use of two independent AO polarization converters [2], [3].

In all-fiber AO devices based on spatial mode coupling rather than polarization mode coupling, much simpler methods for polarization insensitivity can be devised because each spatial mode simultaneously supports two eigenpolarization states [4]. Recently, all-fiber AOTF's based on spatial mode coupling in fused null couplers have been demonstrated [5], [6]. Such devices offer significant advantages over their integrated-optic counterparts due to their low insertion losses ($\sim$0.1 dB), low-acoustic power requirements (<1 μW for $>99\%$ coupling efficiency) and simple construction [5]. The null-coupler AO devices are inherently polarization dependent since the optical beat length of the two relevant spatial modes are different for the two eigenpolarization states. This polarization dependence will need to be eliminated to make a practical filter for WDM applications.

In this letter, we demonstrate polarization-insensitive operation of a null-coupler AOTF by simultaneously applying two acoustic waves. The two waves of different frequencies independently provide phase-matched coupling for each of the individual eigenpolarization states. The resultant unequal frequency shifts for the individual polarization components are compensated by a simple double-pass arrangement, in which light experiencing (say) an up-shift on its first pass through the coupler is down-shifted equally on the second, resulting in no net frequency shift for both polarization components.

The null coupler on which the filter is based is made from two fibers with diameters mismatched to the extent that the resultant coupler gives an extremely small passive coupling efficiency. It can be made by pretapering one of two identical single mode fibers along a short length before both fibers are fused and elongated together to form the coupler. This gives a device with identical ports. Input light in the fiber that was not pretapered excites only the fundamental mode in the narrow waist of the coupler. Light in the other fiber excites only the second-order mode in the waist. In both cases, the light propagates along the waist without further interactions and returns to the original fiber at the other end of the coupler. A flexural acoustic wave propagating along the waist effectively causes a periodic index modulation. When the acoustic wavelength matches the optical beat length of the two modes in the waist, resonant coupling takes place between them. Spectral filtering arises from the wavelength-dependent characteristics of the beat length. The center wavelength of the filtered spectrum can be tuned by control of the acoustic frequency.

The eigenpolarization states of the device are determined by the symmetry of the null coupler; one eigenstate is linearly polarized parallel to the plane of the null coupler (Y-pol.) and the other is orthogonally polarized (X-pol.). In a coupler waist with a circular cross section, X-pol. has a larger beat length than Y-pol. This results in a polarization splitting of $\Delta f(\lambda) = f_y(\lambda) - f_x(\lambda)$ in the acoustic frequency required to couple a given optical wavelength, where $f_y(\lambda)$ and $f_x(\lambda)$ are the phase-matching acoustic frequencies for Y-pol. and X-pol., respectively, at the wavelength λ.

The AOTF demonstrated below is illustrated in Fig. 1. The acoustic transducer is driven by electrical signals with frequencies of $f_x(\lambda)$ and $f_y(\lambda)$, respectively. Input light of arbitrary polarization enters the device in port 1. Both polarization com-

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S. H. Yun, D. J. Richardson, and D. O. Culverhouse are with the Optoelectronics Research Center, University of Southampton, Southampton SO17 1BJ, U.K.

T. A. Birks was with the Optoelectronics Research Center, University of Southampton, Southampton SO17 1BJ, U.K. He is now with the School of Physics, University of Bath, Bath BA2 7AY, U.K.

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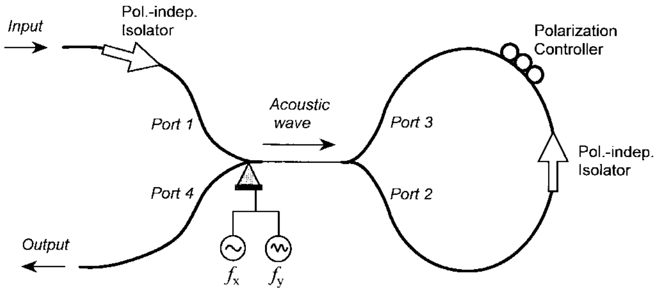

Fig. 1. Schematic diagram of the experimental polarization-insensitive double-pass AO tunable filter.

ponents are coupled to port 2, but undergo different up-shifts in frequency. (Any uncoupled light emerging from port 3 is rejected by the intra-loop isolator.) After propagating through the loop, light of each polarization re-enters the coupler and is coupled a second time, exiting through port 4 with a frequency down-shift. (Again, any uncoupled light is absorbed within an isolator). Providing we ensure that the birefringence within the loop is such that the two eigenpolarizations are not mixed, the frequency shifts associated with the two AO couplings cancel to give zero net frequency shift for each input polarization state. Furthermore, since spectral filtering occurs twice in this double-pass configuration additional benefits are obtained: the spectral bandwidth of the filter is reduced by a factor of 0.75 and, more significantly, a much enhanced spectral side lobe suppression, theoretically as low as -18.6 dB, can be obtained.

We demonstrated the device experimentally as follows. A null coupler with a uniform 8-mm-long waist was fabricated using standard single mode telecommunication fiber. The excess loss of the passive null coupler was $\sim$0.1 dB and the maximum coupling efficiency was -25 dB. An acoustic transducer, formed with a piezoelectric element and an aluminum concentrator horn, was used to excite a flexural acoustic wave within the coupler. The horn was bonded to the null coupler transversely at some distance from the waist.

The single pass polarization characteristics of the AO switch were measured by launching broad band polarized light into the device and measuring the coupled spectrum at port 2 with an optical spectrum analyzer. The center wavelength of both X-pol. and Y-pol. filter responses were obtained and are plotted in Fig. 2. The acoustic frequency splitting $\Delta f(\lambda)$ required to couple a given wavelength was determined to be $\sim$1.5 MHz in agreement with our calculations for a circular coupler waist.

Fig. 3 shows the optical spectra of both eigenpolarization states at (a) the input, (b) in the loop and (c) at the output, when narrow band (<100 kHz) light with $\lambda = 1545$ nm is launched into the device with equal intensities in both polarizations. Electrical signals with frequencies of $f_x = 10.675$ MHz and $f_y = 12.139$ MHz were combined electronically and simultaneously applied to the transducer. The optical spectrum was measured with a Fabry–Perot scanning interferometer (2 MHz resolution). It is clear that the two polarizations have the same optical frequency at the filter output, whereas within the loop the spectrum is split due to the different frequency shifts for the two polarization components.

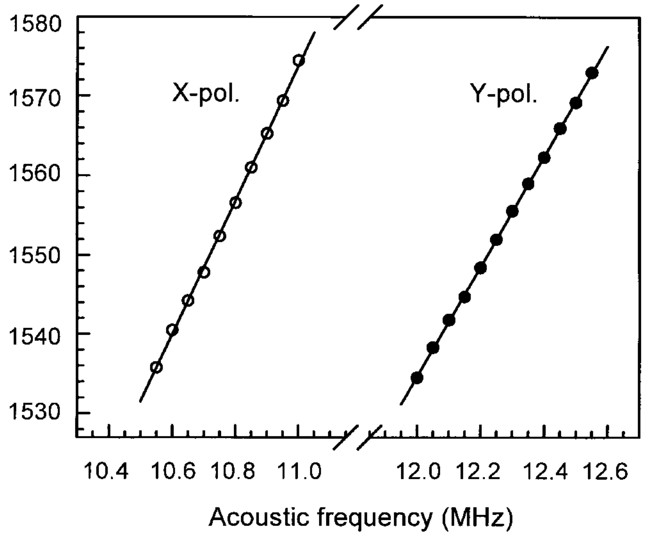

Fig. 2. Variation of centre wavelength with acoustic frequency for both eigenpolarizations.

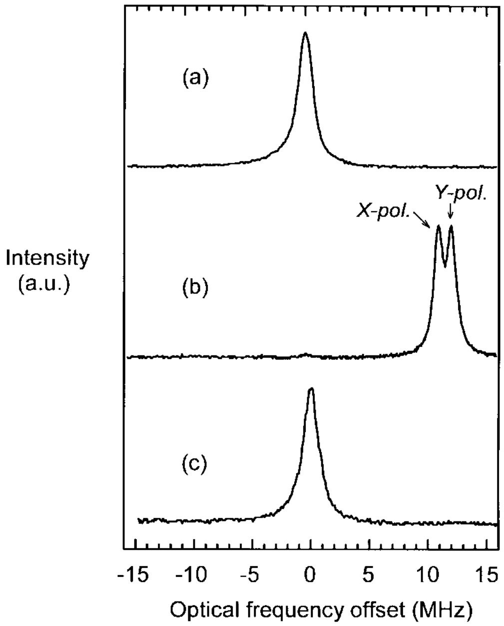

Fig. 3. Optical spectrum (a) in the input, (b) in the loop after the first AO coupling, and (c) in the output after the second AO coupling. There is no net frequency shift in the double-pass scheme.

Fig. 4 shows the spectral filtering characteristics measured with a polarized broad band LED source. Fig. 4(a) and (b) show single-pass coupled spectra centered at $\lambda = 1560$ nm for X-pol ($f_x = 10.835$ MHz) and Y-pol ($f_y = 12.348$ MHz), respectively. These are compared to the double-pass result shown in Fig. 4(c) when the input consists of both eigenpolarization states with equal intensities. The optical bandwidth for single pass was 13.5 and 12.5 nm for X-pol. and Y-pol., respectively. This was reduced to $\sim$9.7 nm for the double pass. The sidelobe suppression was ~ -8 dB for single pass and was enhanced to -17 dB for the double pass. The center wavelength of the filter could be tuned, by control of the acoustic frequencies, over a region covering the entire

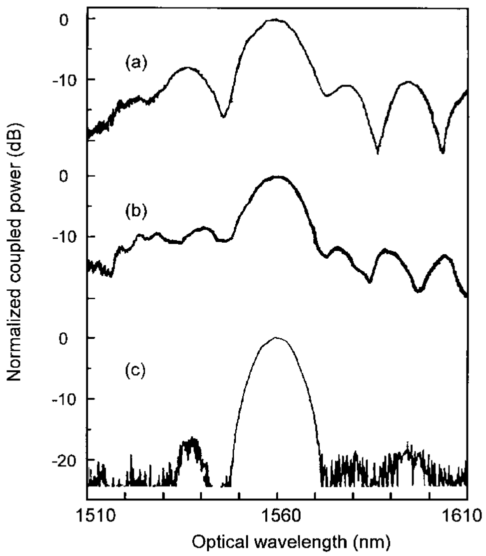

Fig. 4. Spectral characteristics of the filter: (a) single-pass for X-pol., (b) single-pass for Y-pol., and (c) double-pass for X- and Y-pol. with equal intensities.

gain bandwidth of erbium-doped fibers, with similar optical bandwidth and sidelobe suppression.

The total loss of the device was measured to be ~6 dB. This relatively large loss was mainly due to the imperfect AO coupling efficiency (~70% for each polarization states) owing to the poor electrical and acoustic impedance matching of the transducer and the limited voltage output of our drive electronics. The applied RF-drive powers are estimated to be a few milliwatts for both frequencies. Losses of ~2 dB, dominated by the loss of the two isolators (~0.5 dB each), should be realistically achievable with an improved transducer design. The polarization-dependent loss of the double-pass device was measured to be <0.1 dB, clearly validating the principle of the polarization desensitization.

The principal drawback to the technique in our present device relates to polarization crosstalk between the two eigenpolarizations within the null coupler. Even though the polarization frequency splitting was quite large in our device (1.5 MHz, corresponding to a 100-nm separation of resonant optical wavelengths), a significant polarization intensity crosstalk of between −20 and −13 dB was observed at a given wavelength depending on the required operating frequencies. Here, the polarization intensity crosstalk is referred to the coupling efficiency for one polarization state by the acoustic wave which provides ~100% coupling efficiency for the other polarization state. The origin of this effect lies in resonant coupling within the taper transitions which were relatively long (25 mm) for this device. The crosstalk resulted in signal beating in the time domain with a visibility of ~0.1–0.15. A similar problem has been observed in multichannel operations of conventional AOTF's [7]. It should prove possible to reduce the effect significantly in future devices by making the waist of the null coupler more uniform and by shortening the taper transitions [6].

In conclusion, we have demonstrated an all-fiber, polarization-insensitive AOTF based on a null coupler simultaneously excited by two acoustic waves. A polarization dependent loss of less than 0.1 dB is achieved with zero net frequency shift, 9.7-nm bandwidth and sidelobe suppression better than −17 dB. With improved control of the fused coupler waist we believe that, in the future, narrower bandwidth devices should be possible. For example, a 30-mm device operated at 40 MHz should be realizable and would give <1-nm linewidth [6].

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