Low-loss all-fiber acousto-optic tunable filter

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We report significant advances in the development of simple all-fiber, tunable acousto-optic spectral filters based on null couplers. The performance agrees well with theoretical predictions and is attributed to improved control of the coupler uniformity. Furthermore, using a double-pass arrangement, we demonstrate filter bandwidth reduction and improved sidelobe suppression of −20 dB. The double-pass configuration is also shown to double the frequency shifts that are obtainable from such devices. © 1997 Optical Society of America

With the advent of single-mode fiber wavelength-division multiplexed transmission systems, the development of cheap, robust, high-performance tunable bandpass filters for wavelength selection and switching is of prime importance.[1] Fiberized acousto-optic (AO) filters are a promising component for these applications. To date, most attention has been focused on $LiNbO_3$ waveguide devices in which TE and TM modes of the waveguide are selectively coupled by a surface acoustic wave. The main limitation of this, and any other bulk or planar waveguide device, is the optical insertion loss that arises from fiber-to-device coupling. The development of low-loss, all-fiber devices is therefore of great significance. An all-fiber tunable filter based on coupling between the modes of a two-mode fiber by a flexural acoustic wave was recently demonstrated.[2] Similar devices incorporating birefringent fiber were also reported.[3] These designs require relatively high drive powers and are of complex construction, incorporating special fibers, mode filters, and (or) mode converters.

Recently a new type of all-fiber acousto-optic device based on four-port null couplers was demonstrated.[4] Research has concentrated on optimizing this device as a frequency shifter and switch. Insertion losses as low as 0.1 dB and frequency-conversion–switching efficiencies higher than 99% were demonstrated for less than 2 mW rf drive power. However, such components can also be used as tunable filters.[5] To date, the filtering characteristics of the devices that have been fabricated have been poor, with the response exhibiting a number of transmission peaks with roughly comparable strengths[4] [such as those in Fig. 1(a)]. These multiple peaks were attributed to unintentional diameter nonuniformities in the coupler waist, or to the polarization properties of the second mode. In this Letter we report on measurements that confirm nonuniformity to be the limiting effect in the earlier devices and demonstrate improved performance from a more uniform coupler. Furthermore, we demonstrate that a double pass through the filer can further reduce the spectral sidelobes and narrow the spectral transmission passband. This configuration can also be used to double the frequency shift, potentially extending the range of frequency shifts to match those of bulk AO devices.

The null coupler is made from two fibers with diameters that are mismatched to the extent that the resultant coupler does not actually couple any light.[4] This is an extremely wavelength-flattened coupler. Like the wavelength-flattened coupler, the null coupler can be made when one of two identical fibers is pretapered

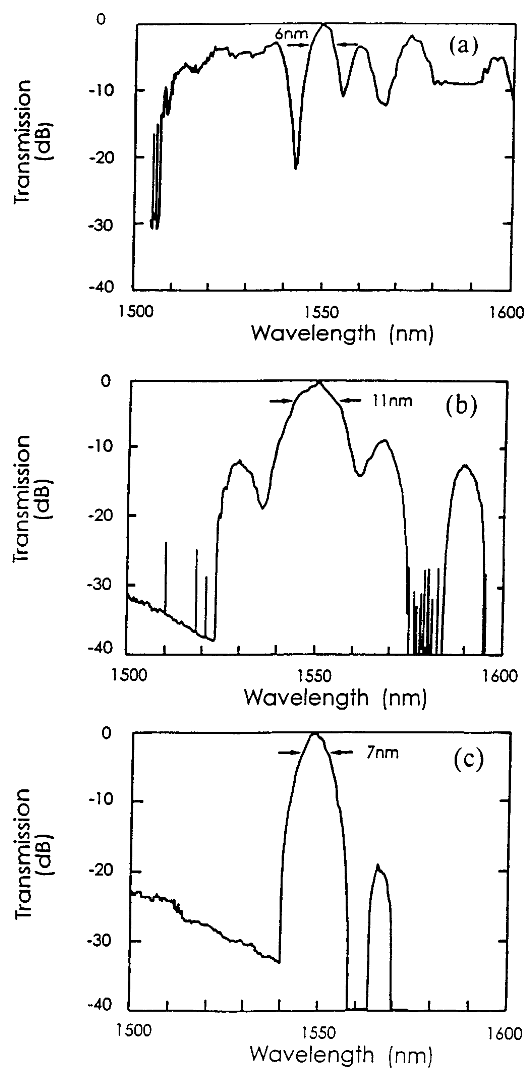

Fig. 1. Coupled spectra of AO filters based on a null coupler with an interaction length of (a) 25 mm, (b) 8 mm, and (c) 8 mm with a double pass.

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along a short length before both fibers are fused and elongated together to form the coupler. This gives a device with identical single-mode ports. Light in one input fiber excites just the fundamental mode in the narrow waist of the coupler. Light in the other input fiber excites just 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 output end of the coupler. A flexural acoustic wave propagating along the fiber causes a periodic refractive-index perturbation in the waist. If a resonance condition is met, that is, if the acoustic wavelength matches the optical beat length between the modes, light can couple between the modes. Furthermore, if the amplitude of the acoustic wave is suitably adjusted, complete coupling is possible: Light enters one fiber, excites just one mode in the waist, is acousto-optically coupled to the other mode, and emerges from the other fiber at the output. The device can function as an optical switch, modulator, or spectral filter, the filter wavelength response being tunable by a change in the applied acoustic frequency.

Two null couplers were fabricated for use in these experiments. The first was similar to that of Ref. 4: It had an interaction length of 25 mm and was designed to be driven at a frequency of 7.6 MHz for 1550-nm light. The second coupler, which was used in the majority of experiments reported here, had an interaction length of 8 mm and was designed to be driven at 14.3 MHz. Because the coupler waist was shorter, improved diameter uniformity was expected. The loss in both devices was less than 0.2 dB, and greater than 99% coupling efficiency could be obtained at a given wavelength for a rf drive power of 2 mW.

The single-pass spectral filtering characteristics of the two AO couplers under appropriate acoustic excitation are shown in Fig. 1. In the case of the 25-mm device, a number of transmission peaks of spectral width 6 nm exist across the 100-nm tuning band, with only a 3-dB contrast between the major and the minor peaks. This poor spectral response is characteristic of all such devices so far reported. In contrast, the response of the shorter device exhibits a single major peak, with a sidelobe suppression of −9 dB, close to that expected for 100% coupling and a perfectly uniform coupler waist [see Fig. 2(a)]. Although the shorter interaction length results in a broader spectral response of ~11 nm (theoretically 9.1 nm) for each peak, the benefits of improved uniformity are clear.

We next investigated tuning of the improved filter with variation of the acoustic frequency. A polarization controller was positioned in front of the filter to control the polarization state of the input light, enabling us to optimize the coupling efficiency. The results are shown in Fig. 3, in which it is seen that the center wavelength of the filter can be continuously tuned between 1525 and 1570 nm for a 5% change in acoustic frequency. One could always obtain greater than 98% coupling by adjustment of the acoustic power.

Because of the inherent low-loss of the filter, multiple passes through the device can be used to obtain both narrowing of the transmission peak and (more importantly) additional suppression of the sidelobes.[6] To investigate this possibility, we constructed a more complex filter with the addition of a circulator and a mirror configured as in Fig. 4. Light passing into the AO coupler from the circulator is frequency shifted and filtered. After reflection at the mirror the signal passes back through the coupler, where it is filtered and frequency shifted once again before exiting through the circulator. The output light has therefore had the acoustic filter response function applied to it twice, resulting in a large suppression in sidelobes and a bandwidth reduction of ≈0.75. The only significant penalty is the additional insertion loss of the circulator (≈2 dB). Note that because the light is frequency shifted twice in this scheme it can also be used to double the obtainable frequency shift.

The theoretical spectral response for the device being tested both for a single pass and for a double pass is shown in Fig. 2, illustrating the benefit of the double pass. For the case of a single pass the expected sidelobe suppression is −9.3 dB, and for a double pass this is increased to −18.6 dB. The experimentally determined double-pass results are shown in Fig. 1(c), in which the spectral width is 7 nm and the sidelobe

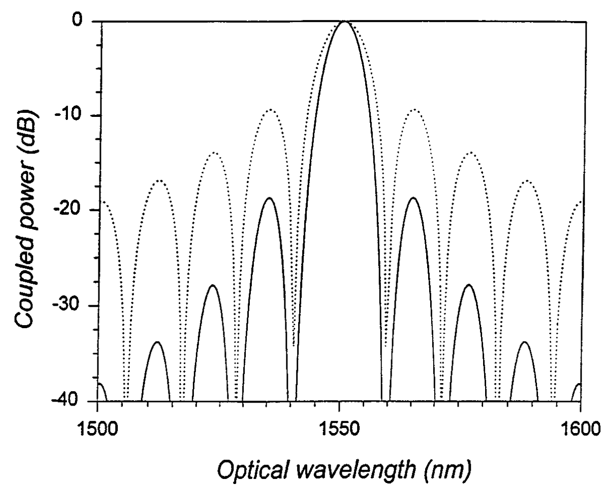

Fig. 2. Theoretical filter response of the 8-mm device for (a) single-pass (dotted curve) and (b) double-pass (solid curve) configurations.

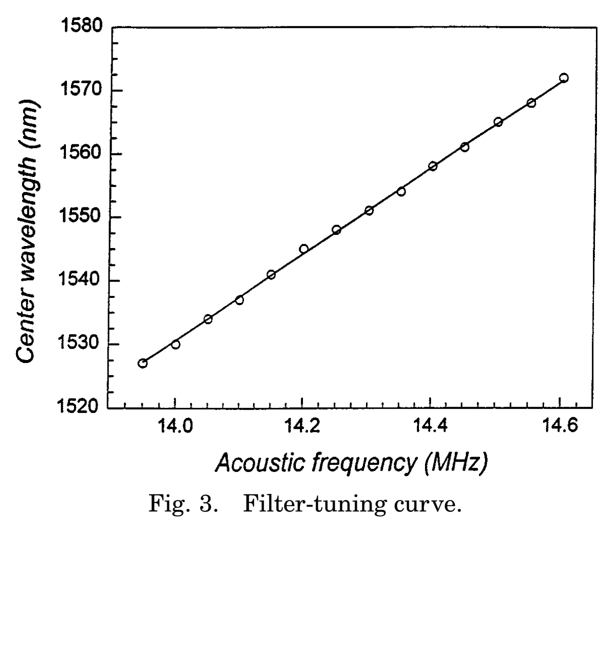

Fig. 3. Filter-tuning curve.

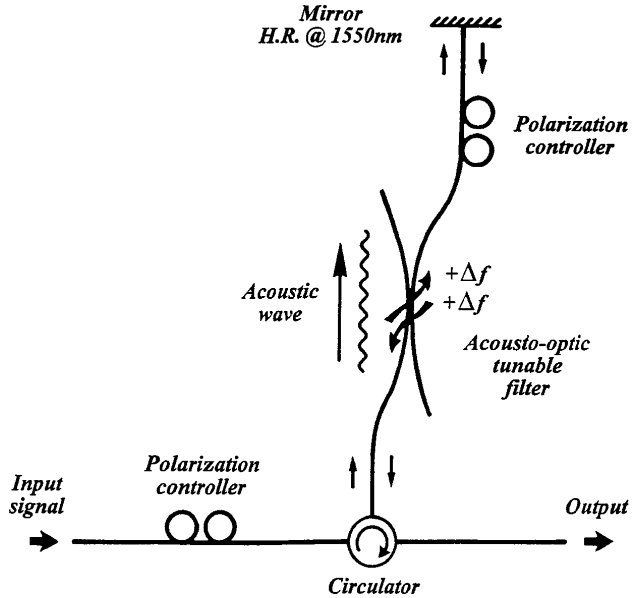

Fig. 4. Double-pass filter configuration. H.R., highly reflective.

suppression is −19 dB, in close agreement with theoretical expectations. The improvement in filter characteristics between the single and the double pass as can be seen when Figs. 1(b) and 1(c) are compared is clear.

Finally, the frequency shifts were measured by mixing the output of the device with light downshifted by 110 MHz in a standard Bragg cell. The detected beat signal at the output was monitored on a rf spectrum analyzer. The frequency shift was 14.3 MHz for a single pass and 28.6 MHz for a double pass, as expected. The carrier suppression was −40 dB, and the image sideband suppression was −35 dB in each case.

We have demonstrated experimentally that great improvements in the spectral filtering characteristics of null coupler AO filters can be obtained: When the diameter nonuniformity of the coupler is restricted (in this case by shortening it), the response approaches the theoretical ideal. Furthermore, we have shown for what we believe to be the first time that we can improve the spectral response of the filter by a double pass through the device. In this instance sidelobe suppression of approximately −20 dB has been demonstrated. We have shown that we can also use the technique to extend the frequency shifts available from such devices. Although the present device is polarization sensitive, with eigenpolarization along the axes of the coupler, more recent research[7] addresses this problem and shows how this effect can be reduced typically from 17 to 0.2 dB.

Our experiments do not represent the limits of the technology. We fully anticipate that, in the future, bandwidths of less than 1 nm should be possible. Improved control of the fused coupler waist should make interaction lengths of 30 mm possible. In this case an AO coupler operating at 40 MHz and based on a double pass will have a filter response of 0.8 nm. The device would similarly be tunable over a broad wavelength range and also have a sidelobe suppression of the order of −20 dB. Furthermore, even better sidemode suppression should be obtainable by use of apodization techniques.

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References

1. C. A. Brackett, J. Selected Areas Commun. **8,** 948 (1990).
2. S. H. Yun, I. K. Hwang, and B. Y. Kim, Opt. Lett. **21,** 27 (1996).
3. W. P. Risk, G. S. Kino, and B. T. Khuri-Yakub, Opt. Lett. **11,** 578 (1986).
4. T. A. Birks, S. G. Farwell, P. St. J. Russell, and C. N. Pannell, Opt. Lett. **19,** 1964 (1994); **21,** 231(E) (1996).
5. D. O. Culverhouse, D. J. Richardson, T. A. Birks, and P. St. J. Russell, Opt. Lett. **20,** 2381 (1995).
6. D. A. Smith, J. J. Johnson, J. E. Baran, V. S. Shah, L. Curtis, and K. W. Cheung, Opt. Lett. **14,** 1240 (1989).
7. D. O. Culverhouse, R. I. Laming, S. G. Farwell, T. A. Birks, and M. N. Zervas, "All fiber 2 × 2 polarization sensitive switch," submitted to Photon. Techol. Lett.