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ALL-FIBRE ACOUSTO-OPTIC TUNABLE FILTER BASED ON A NULL COUPLER

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Abstract
Tunable acousto-optic spectral filters based on null couplers have been improved by making the coupler more uniform. A new double-pass arrangement further narrows the bandwidth, reduces the sidelobes to −20 dB and doubles the frequency shift.

Introduction
With the advent of single-mode fibre WDM transmission systems, the development of cheap, robust, high performance tunable band-pass filters for wavelength selection and switching is of prime importance[1]. Fiberised acousto-optic (AO) filters are a promising component for these applications. To date most attention has focused upon $LiNbO_3$ 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 fibre-to-device coupling. The development of low-loss, all-fibre devices is therefore of great significance. An all-fibre tunable filter based on coupling between the modes of a two-mode fibre by a flexural acoustic wave has recently been demonstrated[2]. Similar devices incorporating birefringent fibre have also been reported[3]. These designs require relatively high drive powers and are of complex construction, incorporating special fibres, mode filters and/or mode converters.

Recently, a new type of all-fibre acousto-optic device based on four port null couplers has been demonstrated[4]. Work has concentrated on optimising the device as a frequency shifter and switch. Insertion losses as low as 0.1 dB and frequency conversion/switching efficiencies higher than 99% have been 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 fabricated has been poor, with the response exhibiting a number of transmission peaks with roughly comparable strengths[4] (such as Fig 1a). These multiple peaks were attributed to unintentional diameter non-uniformities in the coupler waist, or to the polarisation properties of the second mode. In this paper we report measurements that confirm non-uniformity to be the limiting effect in the earlier devices and demonstrate almost ideal performance from a more uniform coupler. Furthermore, we demonstrate that a double pass through the filter can reduce still further 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 fibres with diameters mismatched to the extent that the resultant coupler does not actually couple any light [4]. It is the extreme wavelength flattened coupler. Like the wavelength flattened coupler, it can be made by pre-tapering one of two identical fibres along a short length before both fibres are fused and elongated together to form the coupler. This gives a device with identical single mode ports. Light in one input fibre excites just the fundamental mode in the narrow waist of the coupler. Light in the other input fibre 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 fibre at the output end of the coupler. A flexural acoustic wave propagating along the fibre causes a periodic refractive index perturbation in the waist. If a resonance condition is met - 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 fibre, excites just one mode in the waist, is acousto-optically coupled to the other mode, and emerges from the other fibre 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.

Results

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, was suspended by taper transitions 21 mm long, and was designed to be driven at a frequency of 7.6 MHz for 1550nm light. The second coupler, which was used in the majority of experiments reported here, had an interaction length of 8 mm and 25 mm taper transitions, 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 an 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 1a and b. In the case of the 25 mm device, a number of transmission peaks of spectral width 6 nm exist across the 100nm tuning band, with only 3 dB contrast between the major and 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 2a). Although the shorter interaction length results in a broader spectral response of about 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 polarisation controller was positioned in front of the filter to control the polarisation state of the input light, enabling us to optimise the coupling efficiency. The results are shown in Fig 3, where it is seen that the centre wavelength of the filter can be continuously tuned between 1525 nm and 1570 nm for a 5% change in acoustic frequency. Greater than 98 % coupling could always be obtained 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. 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 ($\approx$ 2 dB). Note that since the light is frequency shifted twice in this scheme, it can also be used to double the frequency shift obtainable.

The theoretical spectral response for the device under test in the case of both a single and 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 1c, where the spectral width is 7 nm and the sidelobe suppression is -19 dB, in close agreement with theoretical expectations. The improvement in filter characteristics between single and double pass as seen by comparing Fig 1b and c 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 an RF spectrum analyser, Fig 5. The frequency shift for a single pass (Fig 5a) was 14.3 MHz and for a double pass (Fig.5b) was 28.6 MHz, as expectated. The carrier suppression was -40 dB and the image sideband suppression was -35 dB in each case.

Conclusion

We have demonstrated experimentally that great improvements in the spectral filtering characteristics of null coupler AO filters can be obtained: by restricting the diameter non-uniformity of the coupler (in this case, by shortening it), the response approaches the theoretical ideal. Furthermore, we have shown for 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 about -20 dB has been demonstrated. We have shown that we can also use the technique to extend the frequency shifts available from such devices.

Our experiments do not represent the limits of the technique and we fully anticipate that, in the future, bandwidths less than 1 nm should be possible: better 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 order -20 dB.

References

[1] C. A. Brackett, J. Selected Areas Commun., **8**, 948 (1990).
[2] S. H. Yun et al, Opt. Lett., **21**, 27 (1996).
[3] W. P. Risk et al, Opt. Lett., **11**, 578 (1986).
[4] T. A. Birks et al, Opt. Lett., **19**, 1964 (1994), erratum in Opt. Lett., **21**, 231 (1996).
[5] D. O. Culverhouse et al., Opt. Lett., **20**, 2381 (1995).

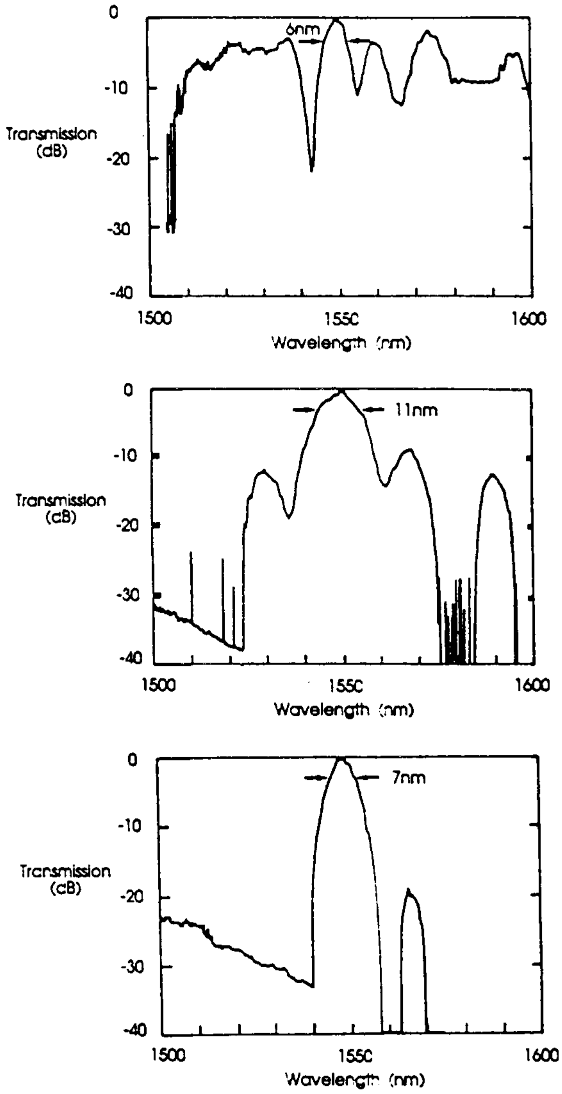

Fig 1 *Coupled spectra of AO filters based on a null coupler with an interaction length of (a) 25 mm, (b) 8 mm, and (c) 8 mm with a double pass.*

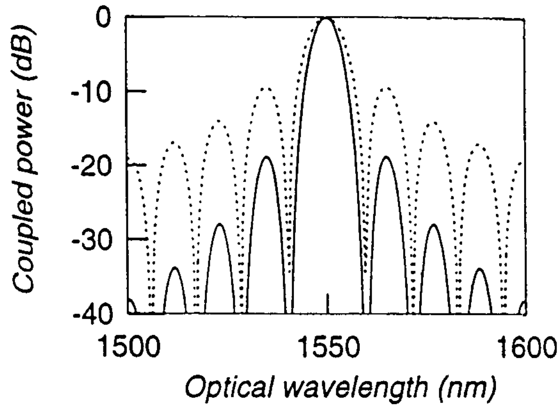

Fig 2 *Theoretical filter response of the 8 mm device for single (dotted line) and (b) double (solid line) pass configurations.*

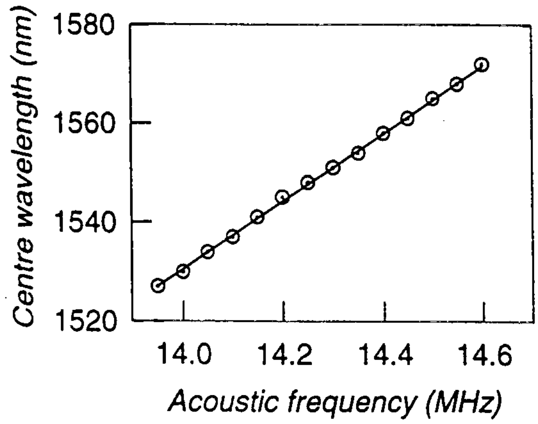

Fig 3 *Filter tuning curve.*

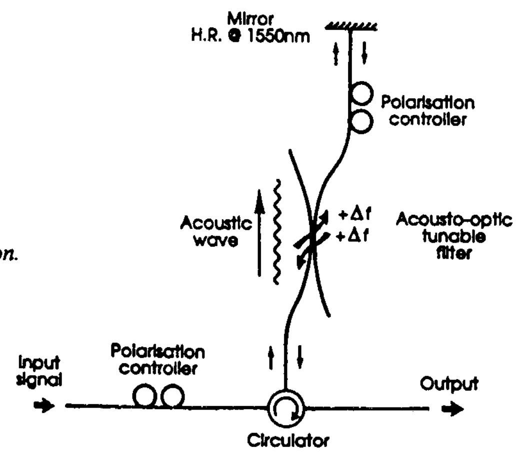

Fig 4 *Double pass filter configuration.*

Fig 5 *RF spectra showing frequency shift components for the 8 mm device in (a) single and (b) double pass configurations.*