San Jose, OFC '94 832.
Feb. '94

FIBRE ACOUSTO-OPTIC FREQUENCY SHIFTER BASED ON A NULL COUPLER

T. A. Birks, S. G. Farwell, P. St.J. Russell and C. N. Pannell

Optoelectronics Research Centre
University of Southampton
Southampton SO9 5NH
United Kingdom

Abstract

A prototype all-fibre acousto-optic frequency shifter, based on a four-port coupler with a null maximum splitting ratio, is reported. Near 100% conversion with 30 dB sideband and carrier suppression is achieved for 1 mW of electrical drive power.

FIBRE ACOUSTO-OPTIC FREQUENCY SHIFTER BASED ON A NULL COUPLER

T. A. Birks, S. G. Farwell, P. St.J. Russell and C. N. Pannell

Optoelectronics Research Centre
University of Southampton
Southampton SO9 5NH
United Kingdom

All-fibre acousto-optic frequency shifters have in the past been based on two-mode fibres[1,2,3], the frequency-shifted light appearing in the second of the two modes. Mode convertors and filters are necessary to separate the residual carrier from the shifted signal and give a single-mode output. Furthermore, the maximum frequency shifts are limited acoustically (by the relatively large fibre diameter) to around 10 MHz. We report the first experimental prototype of a device that promises to solve these problems and requires much less drive power; it is based on a four-port fused taper null coupler.

To make a fused taper coupler, two parallel fibres are heated and stretched together in a small flame. In general, some of the light in one fibre is cross-coupled to the other fibre, with the rest remaining in the first fibre. If the coupler is made from a pair of identical single-mode fibres, the coupling ratio varies cyclically between 0 % and the maximum of 100 % as the coupler is elongated. However, with dissimilar fibres (or with initially identical fibres if one is then pre-tapered), the maximum coupling can be less[4] than 100 %. In what we call an ideal null coupler, the fibres are so mis-matched that the maximum coupling ratio is zero; a passive null coupler does not function as a beam-splitter at all. Light launched in one fibre evolves adiabatically into just the fundamental mode of the cladding-air waveguide at the coupler waist, emerging from the same fibre at the exit (Fig. 1a). Similarly, light launched in the other fibre evolves into the second mode of the waist. This behaviour has been described as "mode splitting" in planar waveguides[5], and critically depends on the optical properties of the coupler's taper transitions.

There is a very important distinction between a null coupler and a standard symmetric coupler with a coupling ratio of 0 %. In the latter, both modes of the coupler waist are excited by an input in one fibre, but they happen to have the right phase relationship at the end of the coupler to return the light to one fibre. This special condition only holds for certain combinations of coupler length and wavelength; for other values, the coupling ratio is not zero. In contrast, in a passive null coupler, an input in one fibre excites only one mode of the waist. The coupler behaves like a pair of non-interacting parallel fibres, with broadband zero splitting for all coupler lengths.

Nevertheless, despite the lack of coupling of light from one fibre to the other, the two modes do overlap in the waist of the null coupler. Hence a travelling flexural acoustic wave can cause resonant coupling between the fundamental and second modes of the waist, with a frequency shift, if the beat-length of the two modes matches the acoustic wavelength. The two modes emerge via different fibres, so if light enters in one fibre then a pure frequency-shifted wave leaves in the other fibre (Fig. 1b). No mode convertors or filters are necessary to separate shifted and unshifted waves, because any residual unshifted light emerges from the first fibre. The device functions as a true four-port all-fibre Bragg cell.

The acousto-optic interaction at the coupler waist is the same as that in the waist of a single tapered fibre, which we have described elsewhere[6]. The two optical modes fill the narrow waist and so overlap completely with the acoustic wave, giving an efficient acousto-optic interaction and hence a low drive power. This contrasts with the two-mode fibre device, where most of the acoustic energy travels near the fibre surface, far from the light buried in the core. Furthermore, frequency shifts of hundreds of MHz are possible because the coupler waist is strongly guiding and can be as thin as 1 μm in diameter.

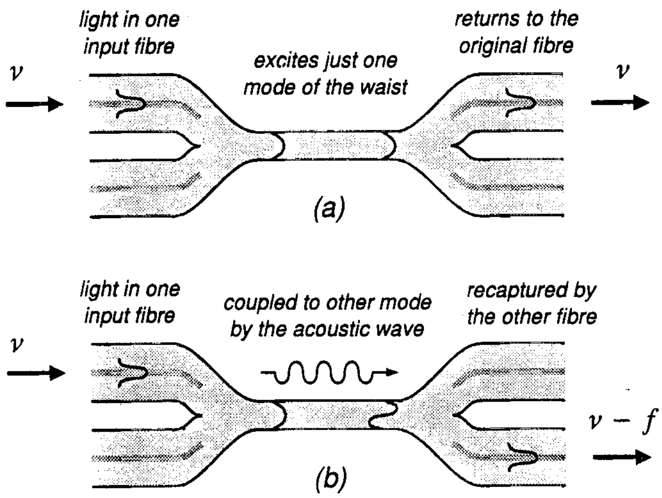

Fig. 1. (a) The evolution of a light wave through a passive null coupler.
(b) The resonant acousto-optic interaction in a null coupler.

We made a null coupler for $\lambda = 633$ nm operation using a pair of dissimilar fibres, with diameters of 60 μm and 80 μm and cut-off wavelengths of 500 nm and 650 nm respectively. The second fibre is not single-mode at 633 nm, but this did not matter as we always launched light into the first fibre. The final coupler had a uniform waist 25 mm long with a circular (and hence reproducible) cross-section of 6 μm diameter, and taper transitions just 25 mm long each. This was possible by using a travelling flame, with a variable range, as the heat source during coupler fabrication[7]. The excess loss was about 0.1 dB and the strongest coupling observed (in the absence of any acoustic wave) was 1:400; maximum coupling ratios as small as 1:6000 were seen in other null couplers.

The flexural acoustic wave was generated using a PZT disc with a concentrator horn, driven by an RF signal. The horn was fixed to the pair of untapered fibres beyond one end of the coupler, in such a way that the acoustic vibration lay in the plane of the coupler (Fig. 2). The acoustic wave travels along the fibres, through the coupler's taper transition, and into the coupler waist. The acoustic wave is focused by the transition, and is unidirectional in the interaction region. Light with a wavelength of 633 nm from a polarised He-Ne laser was launched into one of the input fibres via a polarisation controller. The optical powers emerging from the two output fibres were monitored, while a resonance was sought by changing the frequency of the RF drive.

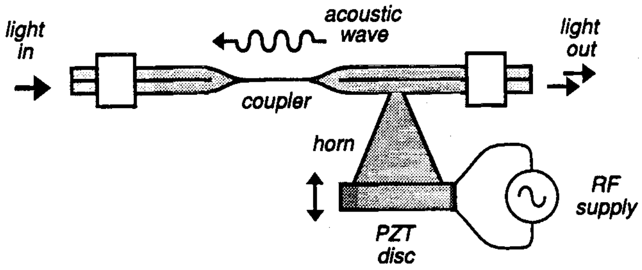

Fig. 2. Construction of the frequency shifter.

An acousto-optic resonance was found at the frequency of 1.851 MHz. Optical output is plotted against RF voltage applied to the PZT disc in Fig. 3 (solid symbols). With polarisation control, over 99 % of the light could be acousto-optically coupled into the second fibre. Although this fibre was not single-mode, the coupled light was carried in its fundamental mode. No attempt was made to optimise the efficiency of conversion from RF electrical drive power to flexural-wave acoustic power. Nevertheless, the RF power required for maximum coupling was only 1 mW, much less than for previous frequency shifters. Since only 170 nW of acoustic power is required in theory, and generation efficiencies of as much as 10 % have been achieved in two-mode fibre^2, there is considerable scope for further improvement.

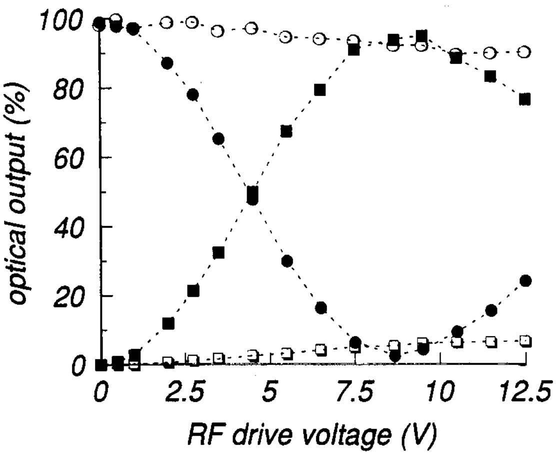

Fig. 3. The throughput (circles) and coupled (squares) optical outputs of the frequency shifter, versus pk-pk drive voltage, for one input polarisation state (solid symbols) and the orthogonal state (hollow symbols).

The frequency shift was measured by inserting the device (taking the output from the second fibre) into one arm of a Mach-Zehnder interferometer. A Bragg cell up-shifted the wave in the other arm by 80 MHz. The detected beat signal was monitored on an RF spectrum analyser, Fig. 4. The main beat component is visible near 82 MHz, corresponding to a frequency down-shift equal to the acoustic frequency. Also visible above the noise floor are beat components with the carrier frequency (80 MHz) and the image sideband (near 78 MHz). These are both about 30 dB below the principal component. The purity of this output was little changed when the drive voltage was reduced from the value for maximum conversion, though of course the total amount of light dropped. The output from the first fibre was unshifted, as expected.

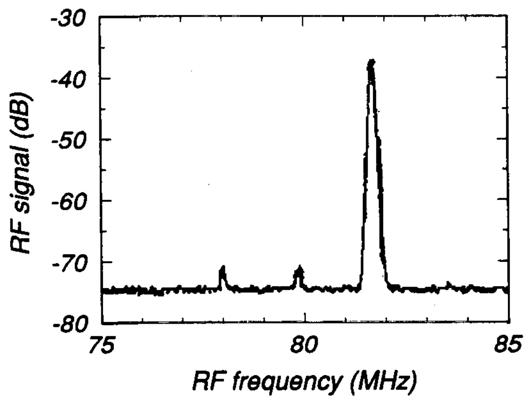

Fig. 4. The RF spectrum of the detected beat signal between the frequency shifter's coupled output and light up-shifted by 80 MHz in a Bragg cell.

The interaction is polarisation dependent. The second set of data (hollow symbols) in Fig. 3 were obtained immediately after the first set, but with the orthogonal polarisation launched into the device by a suitable adjustment of a half-wave plate. There is very little coupling for this polarisation at 1.851 MHz and its resonant frequency was found to lie at 1.795 MHz. The two polarisation states of the second mode in the coupler waist are not degenerate, one being polarised parallel to the spatial lobes in its field distribution, the other being polarised perpendicular to them (in the LP approximation). Hence there are two eigen-polarisations with two different beat-lengths, resulting in two slightly different resonance conditions. The coupler waist, with its large refractive index step between the silica cladding and the surrounding air, is not a weakly guiding waveguide, and this exaggerates the polarisation dependence. The calculated polarisation splitting of 0.08 MHz is of the same order as the measured value.

The frequency shifter is broadband in the sense that a given device can be operated over a very wide range of RF frequencies and optical wavelengths, limited only by the useful single-mode range of the fibre and the frequency response of the PZT disc. However, if (say) the frequency is changed, the wavelength of operation also changes to compensate. Also relevant, then, is "bandwidth" meaning the range of acoustic frequencies the device can operate over once a given optical wavelength has been chosen, and *vice versa*. An unintentional non-uniformity in waist diameter (of the order of just 0.05 μm) led to the measured optical bandwidth being 10 nm for a single polarisation, instead of the theoretical value of 3.5 nm. Indeed, it should be possible to increase the bandwidth further by deliberately making the coupler waist narrower at one end than the other[2]. This would reduce the constraints on optical and RF sources, and make the device less sensitive to its environment. Furthermore, if the bandwidth exceeds the polarisation splitting, there should be a overlap of wavelengths for which the device is effectively polarisation-independent.

Frequency shifts of up to hundreds of MHz are possible by using a narrower coupler waist and a suitable transducer. Operation at communications wavelengths is straightforward by a suitable choice of a pair of fibres. A device with four identical single-mode ports is possible by pre-tapering one of a pair of identical fibres prior to coupler fabrication, to make the fibres sufficiently dissimilar to yield a null coupler. These can of course be standard single-mode fibres; the acousto-optic properties of the device are fixed only when the coupler is made.

The device can also function as an optical switch, modulator or tunable filter (AOTF). Switch and modulator behaviour arises through control of the acoustic amplitude. The filter wavelength is tunable by changing the acoustic frequency, as already demonstrated for the earlier single-taper device[6].

In conclusion, the null coupler device provides a simple and versatile design of low-power frequency shifter, which is ready-made with four single-mode fibre ports.

This work was supported by the U.S. Department of the Air Force through the European Office of Aerospace Research and Development, London.

References

1. B.Y.Kim, J.N.Blake, H.E.Engan and H.J.Shaw, Opt. Lett., **11**, 389 (1986).
2. H.E.Engan, B.Y.Kim, J.N.Blake and H.J.Shaw, IEEE J. Lightwave Technol., **6**, 428 (1988).
3. J.Blake and P.Siemsen, Proc. OFS-9, 301 (1993).
4. D.B.Mortimore, Electron. Lett., **21**, 742 (1985).
5. W.K.Burns and A.F.Milton, IEEE J. Quantum Electron., **11**, 32 (1975).
6. T.A.Birks, P.St.J.Russell and C.N.Pannell, IEEE Photon. Technol. Lett., accepted for June 1994.
7. T.A.Birks and Y.W.Li, IEEE J. Lightwave Technol., **10**, 432 (1992).