Four-port fiber frequency shifter with a null taper coupler

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A prototype of a new design of fiber frequency shifter, based on a special four-port fused taper coupler with a null maximum coupling ratio, is reported. In this coupler the constituent fibers are so dissimilar that the maximum coupling is (ideally) zero. In the presence of a flexural acoustic wave, light is coupled between the fibers, acquiring a frequency shift in the process. Near 100% conversion with 30-dB sideband and carrier suppression is achieved, in an unoptimized device, for just 1 mW of electrical drive power.

All-fiber acousto-optic frequency shifters have in the past been based on fibers supporting two modes. Resonant coupling between the modes occurs when their beat length matches the acoustic wavelength, the coupled light being frequency shifted.[1-3] These devices can also function as tunable filters, switches, and modulators. When they are used as single-sideband frequency shifters, mode converters and filters are necessary to separate the residual carrier from the shifted signal[1] and give a single-mode output. Furthermore, the maximum frequency shifts are limited acoustically (by the relatively large fiber diameter) to ~10 MHz.

We previously reported acousto-optic interactions in the narrow uniform waist of a tapered single-mode fiber.[4] The taper waist is in fact a multimode waveguide, supporting many cladding modes that fill the fiber. Light entering the taper waist in the fundamental mode can be coupled to the second mode (and vice versa), with a frequency shift, by a flexural acoustic wave. There is complete overlap between the acoustic and optical waves, and hence a low acoustic power requirement, in contrast to other schemes.[1-3] The design is versatile because the nature of the interaction region at the taper waist is fixed only when the taper is made, and one can operate it at acoustic frequencies of up to hundreds of megahertz by making the waist diameter as small as a micrometer.

This single taper device suffers from the disadvantage that the frequency-shifted light coupled into the second mode is not guided by the single-mode fiber and is therefore lost. It can be recovered if a tapered two-mode fiber is used, but it is then necessary to incorporate mode converters and filters to yield a single-mode output, as with a frequency shifter made by use of ordinary untapered two-mode fiber.[1]

We describe here a new design of acousto-optic frequency shifter, in which the single fiber taper is replaced with a null taper coupler. This is a fused taper directional coupler that is so phase mismatched that the maximum coupling is zero. The mechanism of the acousto-optic interaction is unchanged, because the waist of the taper coupler is a similar waveguide to the waist of a single taper. However, the frequency-shifted light is not now lost but emerges from one of the coupler's output fibers.

A fused taper coupler, or beam splitter, is made by heating and stretching two parallel fibers together in a small flame. In general, some of the light entering the coupler in one fiber is cross coupled to the other fiber (the coupled wave), while the rest remains in the first fiber (the throughput wave). If the coupler is made from a pair of identical single-mode fibers, any coupling ratio from 0% to the maximum of 100% is possible as the coupler is elongated. With dissimilar fibers (or if one has been pretapered), the maximum coupling can be less[5] than 100%. In an ideal null coupler, the fibers are so mismatched that the maximum coupling ratio is effectively zero; that is, the passive null coupler does not function as a beam splitter at all. Light launched into one fiber evolves adiabatically into just the fundamental mode of the coupler waist, emerging from the same fiber at the exit [Fig. 1(a)]. Similarly, light launched in the other fiber evolves into the second mode of the waist. This behavior has been described as mode splitting in planar waveguides[6] and arises critically from the optical properties of the coupler's taper transitions.

Note the 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 fiber but happen to have the correct phase relationship at the end of the coupler to return the light to the same fiber. This special condition holds only for certain

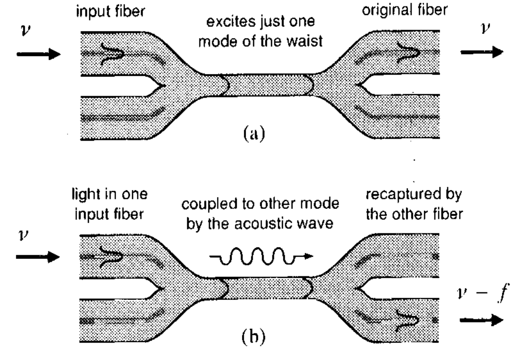

Fig. 1. (a) Evolution of a light wave from one fiber through a passive null coupler, (b) the acousto-optic interaction in a null coupler.

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combinations of coupler length and wavelength; for other values, the coupling ratio is not zero. However, a passive null coupler behaves as a pair of noninteracting fibers, with broadband zero splitting for all coupler lengths.

Despite the lack of interaction between the light waves in the two fibers, they do interpenetrate and overlap at the waist of the null coupler. Hence a traveling flexural acoustic wave can cause resonant forward coupling between the fundamental and second modes of the coupler waist, with a frequency shift, if the beat length of the two modes matches the acoustic wavelength. The two modes emerge via different fibers, so if light enters one fiber then a pure frequency-shifted wave leaves the other fiber [Fig. 1(b); in this case, there is a downshift]. No mode converters or filters are necessary to separate shifted and unshifted waves, because any residual unshifted light emerges from the first fiber.

We made a null coupler for $\lambda = 633$ nm operation using a pair of dissimilar fibers with diameters of 60 and 80 μm and cutoff wavelengths of 500 and 650 nm, respectively. The second fiber was not single-mode at 633 nm, but in our experiments we always launched light into the first fiber and checked that the output from the second fiber was in the fundamental mode. The fibers were held in parallel and then heated and stretched together in a traveling flame. The final waist was 25 mm long, uniform, and approximately 6 μm in diameter, with short taper transitions each 25 mm long. Control of these dimensions was achieved by varying the flame's travel distance during coupler elongation.[7] The waist cross section was circular; this gives a good overlap between the two optical modes, is reproducible, and resembles the waist of a single tapered fiber (which is simple to analyze theoretically[4]). The excess loss was approximately 0.1 dB, and the maximum coupling ratio was 1:400 (maximum coupling ratios as small as 1:6000 were seen in other null couplers).

A flexural acoustic wave was excited in the coupler waist by a piezoelectric (PZT) disk with a concentrator horn, driven by an rf signal. The horn was fixed to the pair of untapered fibers at one end of the coupler (Fig. 2) in such a way that the plane of the acoustic wave coincided with the plane of the coupler. The acoustic wave travels along the fibers, through the coupler's taper transition, and into the coupler waist. This arrangement has the advantages that the acoustic wave is focused by the transition and is undirectional in the interaction region. Light at 633 nm from a polarized He–Ne laser was launched into one input fiber of the coupler via a polarization controller. The optical powers emerging from the two output fibers were monitored, while we sought a resonance by changing the rf frequency.

An acousto-optic resonance was found at a frequency of 1.851 MHz. Optical output is plotted in Fig. 3 against the peak–peak rf voltage applied to the PZT disk. With polarization control, greater than 99% acousto-optic coupling into the second fiber was possible. Although this fiber was not single mode, we found that the coupled light was carried in its fundamental mode. The rf power required for maximum coupling was as low as 1 mW, much less than for previous frequency shifters.[1] Even so, we made no attempt to optimize the efficiency of conversion from rf electrical drive power to flexural-wave acoustic power; since the theoretical acoustic power required is 170 nW, there is considerable scope for improvement.

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

The polarization dependence is undesirable but can be masked by making the coupler waist slightly nonuniform. This broadens the resonance for each polarization, because the resonance condition now varies along the waist. If this broadening exceeds the polarization splitting there will be an overlap where both polarizations are efficiently frequency shifted. Such a frequency shifter would behave in an effectively polarization-insensitive manner for restricted combination of optical wavelength and acoustic frequency.

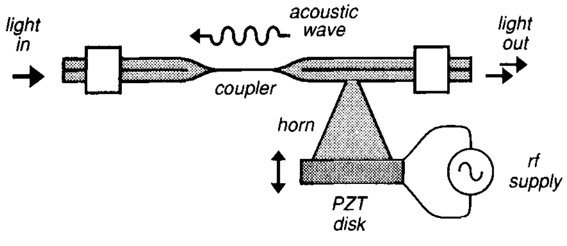

Fig. 2. Assembly of the frequency shifter.

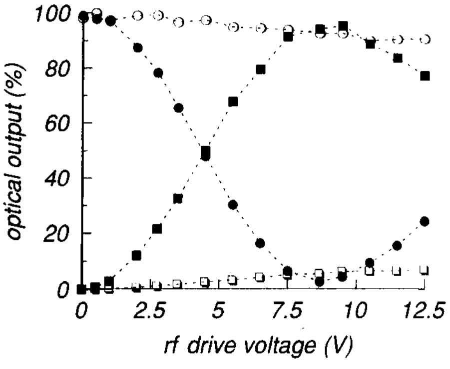

Fig. 3. Throughput (circles) and coupled (squares) optical outputs of the frequency shifter versus rf drive voltage, for one input polarization state (filled symbols) and the orthogonal state (open symbols).

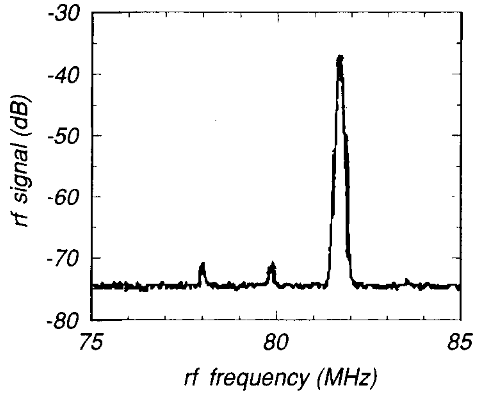

Fig. 4. Rf spectrum of the detected beat signal between the frequency shifter's coupled output and light upshifted by 80 MHz in a Bragg cell.

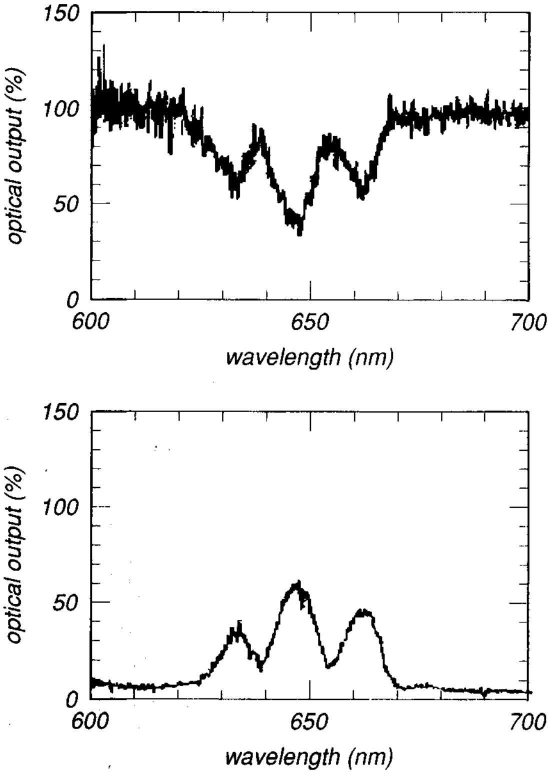

Fig. 5. Normalized optical output spectra of the device for (a) throughout light and (b) coupled light.

We measured the frequency shift by inserting the device (taking the output from the second fiber) into one arm of a Mach–Zehnder interferometer. A Bragg cell upshifted the wave in the other arm by 80 MHz. The detected beat signal was monitored on an rf spectrum analyzer (Fig. 4). The main beat component is visible near 82 MHz, corresponding to a frequency downshift 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). There are both approximately 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 fiber was unshifted, as expected. In contrast with the situation depicted in Fig. 1(b), here the input light excites the second mode of the coupler waist and interacts with a counterpropagating acoustic wave. However, this reverses the sign of the frequency shift twice, so the net result is again a downshift.

The device can also function as an optical switch, modulator, or tunable spectral filter. The filter wavelength is tunable by a change in the acoustic frequency.[4] To measure the behavior of the device as a filter, we launched unpolarized white light into the input fiber and fed the outputs to an optical spectrum analyzer. The normalized spectra obtained for an acoustic frequency of 1.860 MHz are given in Fig. 5. The spectra are complementary as expected from power conservation; the device acts as a notch filter in the throughput path and as a bandpass filter in the coupled path. The three-peaked structure of the spectra is believed to be due to the polarization properties of the set of second modes in the coupler waist. The 10-nm width of each peak is greater than the expected width of 3.5 nm; a longitudinal nonuniformity of 0.02 μm in the diameter of the coupler waist is sufficient to account for this. Indeed, one can increase the spectral bandwidth if necessary by deliberately making the coupler waist nonuniform, as discussed above in the context of polarization dependence.

As with the single taper device,[4] frequency shifts of up to hundreds of megahertz are possible by use of a narrower coupler waist. Operation at communications wavelengths is straightforward by a suitable choice of a pair of fibers. A device with four identical single-mode ports is possible by pretapering one of a pair of identical fibers before coupler fabrication,[5] making the fibers sufficiently dissimilar to yield a null coupler. Although the narrow coupler waist might at first sight be expected to be mechanically weak, it is significant that standard fused taper couplers (with only slightly greater waist diameters) are now in routine use as robust beam splitters and wavelength-division multiplexers. In conclusion, the null coupler device provides a simple and versatile low-power frequency shifter, ready-made with four single-mode fiber ports.

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