completely with respect to $M = 1$. This was observed only after an artificially three times intensity magnification of the

Fig. 2 *NS-PCM and video subtraction as quality check criterion*
Right: Half picture 'BALTIMOR'; 5 bit NS-PCM ($K = 8$; $L = 5$; $M = 2$)
Left: Pixel by pixel subtraction of 8-bit PCM from 5-bit NS-PCM

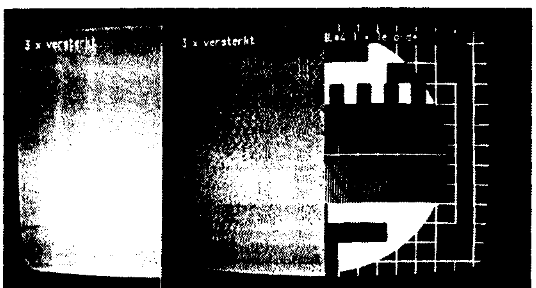

Fig. 3 *Correlation noise cancelling*
Right: Half picture 'CIRCLE'; 4 bit NS-PCM ($K = 8$; $L = 4$; $M = 1$)
Middle: Three times magnified correlation noise ($K = 8$; $L = 4$; $M = 1$)
Left: Three times magnified video subtraction noise ($K = 8$; $L = 4$; $M = 2$)

pixel errors and by using 'CIRCLE'. The processed pictures for $L = 3$ and $M = 2$ (not shown) give quite acceptable results. They should be valuable for guarding purposes. Further increase of M above 2 makes no sense because of the domination of F_M from eqn. 1 especially for very low L values. It may be possible to use 'diagonal noise'. Changing the 1-sample (pixel) delay time, caused by the DSM accumulator register, into one video line delay time plus or minus one pixel time within each DSM gives rise to 'diagonal noise'. For $L = 3$ or 4 additional improvements are expected. Inter-field combining is also possible.

Applications: TV broadcast quality preservation for $L = 5$ enables bit rates < 106 Mbit/s (PAL: < 70 Mbit/s). Robustness, no demodulator propagation errors and simplicity make this code superior to other differential-like PCM codes.[6] A video signal with a baseband width < 14 MHz can be transmitted with 140 Mbit/s. This satisfies HDTV transmission for future broadband ISDN (BISDN) in a cost effective way. It also offers a better and easier antialiasing technique than in Reference 7 for new computer and radar displays (VGA). In digital TV sets the field memory size can be reduced. It can also be used for numerous non-video application with OS, e.g. speeding up tape recording for higher resolution, control systems, etc.

Conclusions: The novel NS-PCM, as sub-band video coding, offers a much higher code efficiency than PCM and even DPCM. The code is absolute, and is therefore robust and very cost effective. L-bit NS-PCM evoked from K-bit PCM has the potential to create at least $L + 3$ bit PCM picture quality for $K - L \geq 3$. With $M = 2$ correlation noise can easily be removed. Only an unchanged L-bit PCM decoder is required. NS-PCM can benefit a wide display area such as TV, HDTV, computer and radar, etc., for video processing and transmission.

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DEMONSTRATION OF BIREFRINGENT OPTICAL FIBRE FREQUENCY SHIFTER EMPLOYING TORSIONAL ACOUSTIC WAVES

Indexing terms: Fibre optics, Acoustic waves, Frequency shifters, Optical fibres

A fibre-optic frequency shifter utilising torsional acoustic waves to produce a travelling perturbation which couples the polarisation modes of a linearly birefringent optical fibre is demonstrated. The shift in optical frequency was 3·195 MHz and an optical coupling efficiency of 6% was obtained with 780 mW of electrical power.

The production of a continuous heterodyne carrier at a suitable frequency for signal processing is an essential feature of many optical fibre sensor systems.[1] An optical frequency shifter in fibre form, as opposed to a bulk-optic device such as a Bragg cell, is a highly desirable component. The development of such devices has attracted a large number of workers in recent years.[2–7] The main elements of a fibre-optic frequency shifter are, an optical fibre which in its unperturbed state supports two initially orthogonal optical modes and a means of inducing a travelling perturbation in such a way that in the perturbed state, optical power can be efficiently exchanged between the modes.

The device presented utilises highly linearly birefringent fibre, rather than two-spatial moded fibre,[4] as this will be easier to incorporate into existing sensor systems. The travelling perturbation is an acoustic wave, excited on the free fibre, rather than on a substrate with which the fibre is in close contact,[2] to exploit the greater concentration of acoustic energy in the vicinity of the fibre core. Travelling acoustic waves which may be excited on a rod fall broadly into three categories: longitudinal, flexural and torsional. Longitudinal modes produce no mode coupling. The flexural mode of lowest order is inherently incapable of yielding a birefringent fibre frequency shifter of high efficiency.[5,8] The coupling coefficient has been derived for a fundamental torsional mode in terms of its peak angular displacement. The use of such a mode to produce a frequency shift in a birefringent fibre is reported.

Utilising coupled mode theory,[9] the transfer of power between two (or more) optical modes by a travelling acoustic perturbation may be analysed. If the two modes, in this case the polarisation eigenmodes, have associated amplitudes $A_1(z)$ and $A_2(z)$, then initial conditions $A_1(0) = 1$ and $A_2(0) = 0$ are assumed, i.e. only one eigenmode is populated at the start of the interaction region. In terms of a coupling coefficient κ for a copropagating fundamental torsional mode, the fraction of power coupled from mode 1 to mode 2 in an interaction length z is given by

$$P(z) = \left|\frac{A_2(z)}{A_1(0)}\right|^2 = \frac{|\kappa|^2}{|\kappa|^2 + \left(\frac{\Delta\beta}{2}\right)^2} \sin^2\left\{z\sqrt{\left[|\kappa|^2 + \left(\frac{\Delta\beta}{2}\right)^2\right]}\right\} \quad (1)$$

Complete power transfer $[P(z) \equiv 1]$ can only occur if $\Delta\beta \equiv \beta_1 - \beta_2 - K \equiv 0$. β_1 and β_2 are the propagation constants of the two optical modes and K is the angular wavenumber of the perturbation. This is known as the longitudinal phase matching condition and is equivalent to matching the spatial period of the perturbation, Λ, to the beat length between the two modes, L_B. The travelling perturbation gives rise to a frequency shift in the coupled light, given by

$$\Delta\omega = \omega_2 - \omega_1 = \Omega \operatorname{sgn}(\beta_2 - \beta_1) \quad (2)$$

where ω_2 and ω_1 are the optical frequencies associated with modes 1 and 2 of the fibre, respectively, and Ω is the angular frequency of the perturbation. The frequency shift is of equal magnitude but opposite sign for a counterpropagating acoustic wave. Following the method of Pannell,[5,8] the coupling coefficient, and hence the angular displacement, Θ, required for complete coupling by a torsional perturbation may be derived

$$\kappa \approx k_0 \Theta(n_1 - n_2) \approx \frac{2\pi\Theta}{L_B} \qquad \Theta(100\%) \approx \left(\frac{L_B}{4z}\right) \quad (3)$$

k_0 is the free space optical wavenumber, n_1 and n_2 are the effective indices for the two modes. For example, if L_B = 1·2 mm and z = 50 cm then $\Theta(100\%)$ = 0·6 mrad, which corresponds to a peak surface displacement of 37·5 nm (assuming fibre radius, a = 62·5 μm). For comparison, from[5,8] the fibre displacement required for a flexural wave for 100% coupling of polar eigenmodes for fibre of the same radius and length (optical wavelength = 632·8 nm), d = 7·1 μm, that is ~190 times greater than for the torsional wave.

The configuration utilised for the generation of torsional waves on an optical fibre is shown in Fig. 1. The configuration consists of a small length of fibre joined to the main fibre at right angles; joint 1. A flexural wave is then excited on this side fibre, using a piezoelectric plate resonator and silica horn acoustic amplifier, attached at the distal end of the side-fibre; joint 2. At joint 1 the flexural wave gives rise to bidirectional, travelling, torsional waves on the main fibre.

The main advantage of using torsional, rather than flexural, waves to couple optical power between the eigenmodes is the greatly increased coupling efficiency, combined with less stringent requirements for joining the transducer to the fibre. This is because, for optimum coupling, a flexural wave transducer

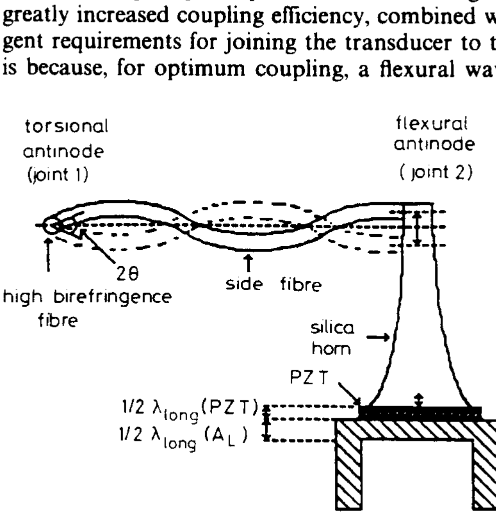

Fig. 1 *Torsional wave generation*

must be aligned such that the plane of vibration is along the bisector of the birefringence eigenaxes. The joining of a silica horn or side fibre inevitably gives rise to stress within the fibre. Joining at 45° to the fibre eigenaxes is optimal for coupling the eigenaxes. Built-in stresses thus give rise to a maximum degree of undesirable static coupling of the modes. In the torsional case there is no 'plane of vibration' to align. It is thus permissible to join the side-fibre at a point directly in line with one of the eigenaxes, giving a minimum of static coupling.

The acoustic frequency required to satisfy phase matching may be simply calculated from the torsional wave velocity

$$c_{tors} = \sqrt{\left(\frac{G}{\rho}\right)}$$

where G is the shear modulus and ρ is the density. For the following fibre parameters: G = 31·2 GPa, $\rho = 2{\cdot}20 \times 10^3$ kgm^{-3}, c_{tors} = 3·77 kms^{-1} and for a highly birefringent monomode fibre with a beat length of 1·2 ± 0·05 mm, the corresponding torsional frequency is ν_{tors} = 3·14 ± 0·13 MHz. For comparison ν_{flex} = 0·20 ± 0·02 MHz.

The fibre utilised in experiments was a York Technology highly linearly birefringent monomode optical fibre of outer diameter 125 μm. The beatlength of this fibre was measured by launching linearly polarised light at 45° to its eigenaxes and observing the polarisation dependent Rayleigh scattered light emerging from the side of the fibre. The spatial period of the beat pattern thus observed, equal to the fibre beatlength, was measured with a travelling microscope. It was found to be L_B = 1·2 ± 0·05 mm (optical wavelength = 632·8 nm). The silica horns were formed by drawing down short lengths of 4 mm diameter silica rod to a tip diameter of ≈300 μm.

The torsional wave generator described formed the basis of a frequency shifter and was incorporated into one arm of a Mach–Zehnder interferometer for evaluation. The highly birefringent fibre was supported such that the device comprised a total interaction length of 600 mm of fibre stripped of its plastic buffer coating, bounded by lengths of unstripped fibre, with the coating acting as acoustic absorbers at either end of the interaction region. The torsional wave excitor was attached close to one end of the stripped section to give a larger interaction length for forward propagating torsional waves than backward propagating waves. The heterodyne interferometric test configuration is shown in Fig. 2. The

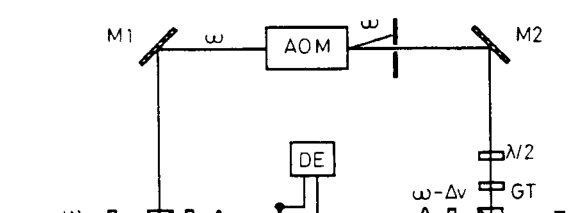

Fig. 2 *Shifter evaluation configuration*

S: optical source; GT: Glan–Thomson polariser
BS1/2: beamsplitters; L: lens; $\lambda/2$: halfwave plate
TFS: torsional wave fibre frequency shifter
DE: drive electronics; M1/2: mirrors; PD: detector
AOM: acousto-optic modulator (Bragg cell)

optical source was a helium–neon laser operating at a wavelength of 632·8 nm. The light from this source passed through a Glan–Thomson polariser to ensure it was linearly polarised prior to being amplitude divided by the beamsplitter. One of the beams was injected into the fibre through a halfwave plate such as to populate only one eigenaxis of the fibre (slow axis, say). As this light passed through the fibre, the action of the torsional wave is to couple light to the other eigenmode (fast axis) imparting a frequency shift $\Delta\nu$. The light exiting the fibre was collimated and passed through a second Glan–Thomson polariser, oriented to transmit only the frequency shifted light coupled to this (fast) eigenmode. The reference path beam traversed a bulk acousto-optic frequency shifter (Bragg cell) which imparted a 40 MHz shift. This light then passed through a halfwave plate and polariser oriented to give a linear state of the same azimuth as the shifted light. The two beams were then recombined at a second beamsplitter and mixed on the surface of an avalanche photodiode.

The frequency spectrum of the output from the detector was investigated using a spectrum analyser. For the ideal case of zero static coupling and 100% dynamic coupling by a monodirectional torsional wave, a single frequency component at a frequency of 40 MHz—$\Delta\nu$ (slow → fast axis coupling is downshift) would be present in the spectrum. In practice three components appear in the spectrum; an unshifted component at the Bragg cell frequency, caused by static coupling of the eigenmodes (principally owing to stress at joint 1), the desired (down) shifted component caused by the bidirectional generation of the torsional waves.

Optimisation of the coupling, by varying the drive frequency to most accurately match the torsional wavelength to the fibre beatlength, gave an optimal drive frequency of 3·195 MHz. Fig. 3*a* shows a spectrum corresponding to upshifting (fast to slow axis), and Fig. 3*b* shows a trace corresponding to downshifting (slow to fast axis). The maximum coupling efficiency achieved was 6%, with an electrical drive power of 780 mW to the piezoelectric transducer. Efficiency

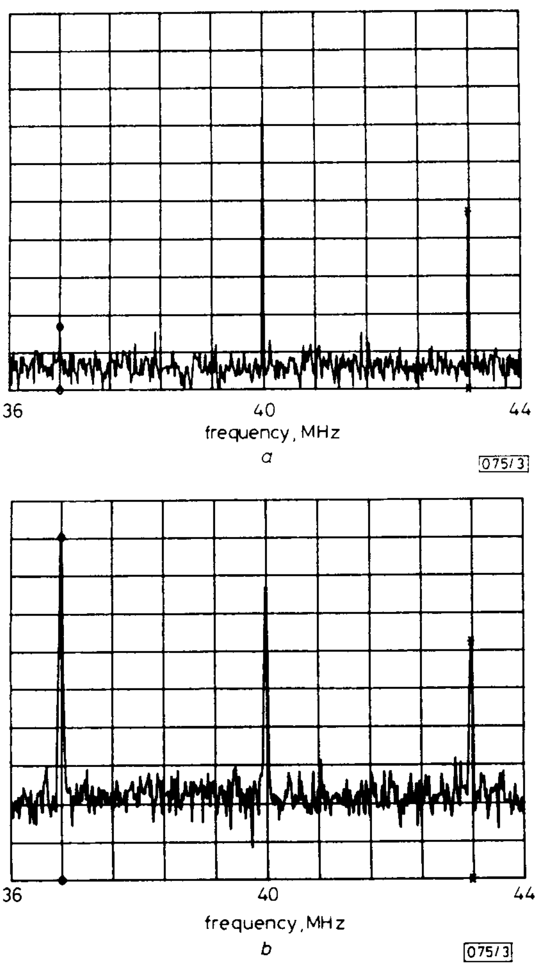

Fig. 3 *Coupling from output spectra*

Drive frequency = 3·195 MHz
a Upshift
b Downshift

may be increased by either increasing the electrical power, increasing the interaction length or by using multiple torsional wave generators attached to the fibre at quarter acoustic wavelength spacing and excited with a 90° phase lag between each successive pair. This should also reduce the counterpropagating component. Following the method of Engan *et al.*[10] the efficiency of utilisation of the acoustic power generated by the piezoelectric plate/silica horn may be estimated. Using the dimensions of the present configuration an efficiency of only a few percent is obtained. Enhanced optical conversion efficiency may thus be achieved by optimisation of the acoustic design.

It has been demonstrated that torsional acoustic waves are a viable method of effecting the mode coupling required in a birefringent fibre frequency shifter. If the conversion efficiency can be maintained at 100%, no additional components are necessary to separate the shifted and unshifted components. At lower coupling efficiencies separation is achieved with simple polarisation components.

Acknowledgments: This research was sponsored by the United States Air Force Office of Scientific Research (AFSC), under Contract F49620-88-C-0123.

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ELECTRON MOBILITIES IN MOS CHANNELS FORMED ALONG ANISOTROPICALLY DRY ETCHED ⟨110⟩ SILICON TRENCH SIDEWALLS

Indexing terms: Electron mobility, Metal oxide semiconductor structures and devices

Experimental silicon trench MOSFET structures were fabricated and used to estimate electron mobilities in MOS channels formed along ⟨110⟩ trench sidewalls. A channel electron mobility approaching 87% of its bulk value can be obtained. These results were derived from a novel trench fabrication process, measured MOSFET drain current–voltage characteristics and accurate two-dimensional device simulations of MOSFET transfer characteristics.

Introduction: Advanced ULSI and high-voltage device technologies are increasingly utilising trench-based structures for fabricating memory cells,[1] active signal and power devices,[2–4] and isolation structures.[5,6] High cell packing density and feasibility of 3D-integration are the key factors in the development and application of trench technologies. Power MOSFETs with significantly lower on-state resistance R_{on} are