differentiators compare favourably with the state of the art differentiators of Kumar and Dutta-Roy [6].

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## NOVEL POLARIMETRIC FIBRE DEVICE FOR INTERROGATING 'WHITE-LIGHT' INTERFEROMETERS

M. G. Xu, M. Johnson, M. Farhadiroushan and J. P. Dakin

*Indexing terms: Optical sensors, Polarisation, Optical fibres*

A novel, in-line, polarimetric fibre interrogator for 'white-light' interferometry is described. It consists of two equal lengths of polarisation-maintaining fibre, spliced with their polarisation axes orthogonal. The interferometer path difference is thermally tuned over the free-space equivalent of ±180 μm to allow matching to a remote sensor interferometer.

*Introduction:* 'White-light' interferometry (WLI) has, over the past few years, become an important fibre sensing technique [1–3]. It provides a means of identifying both the absolute optical interference fringe order and the residual phase angle in a remote, unbalanced interferometer. In a typical system, a broadband source is coupled through a remote sensing interferometer, such as a Fabry–Perot, with an optical path difference (OPD) $d$. This acts as an optical filter which imparts a periodic modulation on the initially smooth spectrum, the pitch of which characterises the OPD of the sensor. In a time-domain description of the effect, light beams proagating via the two paths of the interferometer are only correlated if the light in the shorter path is subsequently delayed by a time $2d/v_g$, where $v_g$ is the group velocity in the interferometer. If a value of $d$ is chosen which is significantly larger than the correlation length of the broadband source, then, without such a compensating delay, small variations in $d$ will not cause visible interference fringes in the integrated signal.

If, however, the optical signal is then passed through a second interferometer, whose path imbalance can be scanned, then high-visibility interference fringes will be detected when the *magnitude* of the path difference closely matches that in the remote interferometer. An independent measurement of the local delay thus allows determination of the magnitude of the unknown remote delay, free from ambiguities. The technique can give high accuracy, but it generally requires moving parts in the readout interferometer (e.g. the scanned Michelson [1]) or involves a relatively complex optical spectrometer arrangement (e.g. a dispersive element plus CCD detector).

We present a new method of constructing a thermally-scanned polarimetric interferometer, using two, nominally-equal, lengths of polarisation-maintaining (PM) fibre, spliced together with their polarisation axes at 90°. The arrangement is essentially that of the compensated polarimetric interferometer which has been used for differential sensing [4]. If not mechanically strained, the OPD between the two polarisation modes in the polarimetric interferometer depends primarily on the temperature difference $\Delta T = T_1 - T_2$ between the two fibre lengths. By scanning the temperature difference, a controllable differential mode delay can be generated, for matching the OPD of the remote interferometer. The advantages of this technique over other methods are that the readout interferometer is a single length of fibre, without any moving parts, and the whole system may be spliced into an optically efficient and compact unit. In addition, operation is possible in wavelength regions where detector arrays are less readily available, and the single small-area detector possible with this technique offers lower noise than with self-scanned arrays.

*Experiment:* Fig. 1 depicts the thermally-scanned, in-line, fibre WLI interrogation system. Light from a 1550 nm fibre-pigtailed ELED, of $1/e^2$ bandwidth ±42 nm, is coupled, via a directional fibre coupler into a Fabry–Perot interferometer, having a separation $d$, to simulate a remote sensor. The power level at the sensor was 4 μW. The Fabry–Perot cavity was formed between the end face of a singlemode fibre and a reflective glass block mounted on a positioner. The rear surface of the block was rough-ground and painted to avoid spurious reflections. The low Fresnel reflectivity at each surface (<4%) meant that the Fabry–Perot effectively acted as a low finesse, two-beam (rather than multiple-beam) interferometer. The effective delay time of the sensor head was therefore $2d/c$, where $c$ is the velocity of light.

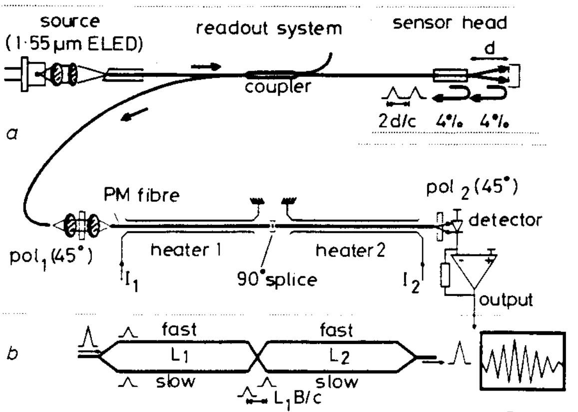

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**Fig. 1** *Schematic diagram of thermally-scanned in-line fibre white-light matched interferometry, and illustration of fast and slow propagation paths in 90°-spliced fibre lengths*

*a* Schematic diagram
*b* Illustration of fast and slow propagation paths

The receiving polarimetric interferometer was formed from two lengths ($L_1 = 10097$ mm, $L_2 = 10073$ mm) of PM fibre (York Ltd. HB1550) with beatlength 3·06 mm. In our case, $L_1$ and $L_2$ were first matched to within 24 ± 0·5 mm, giving a mismatch of only seven fringes when the fibres are of equal temperatures. Initial matching was carried out using a commercial York S18 chromatic dispersion instrument. Subsequent shortening of one fibre reduced the mismatch to less than one fringe. Equal optical power was launched into the fast and slow eigenaxes, i.e. there were equal intensity beams travelling in the fast and slow states. At the central splice, fast and slow axes are interchanged, so that for equal lengths and temperatures ($L_1 = L_2$, $T_1 = T_2$) the differential delay is zero. Each length of PM fibre was contained within separate stainless steel tubes ($ID = 0{\cdot}406$ mm, $OD = 0{\cdot}635$ mm, resistance = 25 Ω), which could be heated by electrical current.

The detected power transmitted through an analyser aligned at 45° to the eigenaxes was measured, as a function of the temperature difference, using a digital oscilloscope. The receiver consisted of an InGaAs photodiode and 500 MΩ transimpedance amplifier.

*Discussion:* In the PM fibre the propagation delays of fast and slow eigenmode are $Ln_f/c$ and $Ln_s/c$, where $n_f$ and $n_s$ are the group refractive indices. Before switching fast and slow eigenmodes, after their passage through the first fibre, the path difference between the two modes is $D = L_1B_1/n_{av}$, where $B_1 = n_f - n_s$ is the modal birefringence of this fibre, and $n_{av}$ is the average group refractive index. This is equivalent to that of the Michelson interferometer used in a conventional mechanically scanned system. After switching fast and slow eigenmodes, followed by passage through the second fibre, the path difference becomes

$$D(T_1, T_2) = \frac{L_1B_1(T_1)}{n_{av}(T_1)} - \frac{L_2B_2(T_2)}{n_{av}(T_2)}$$

By varying their temperature $T_1$, $T_2$, and hence the group indices of fast and slow modes, the total differential path could be scanned through positive and negative values. A range of ±120 fringes (equivalent to a free-space OPD of $\sim \pm 180\,\mu$m) was obtained for a temperature difference of 80°C. This is equivalent to mechanically scanning the mirror of a Michelson interrogation interferometer by $\pm 180\,\mu$m. Although the beams are CW, the relative delays are emphasised in Fig. 1 by showing timing 'markers'. When the path differences of two interferometers were closely matched, a good fringe contrast was observed (Fig. 2), despite the use of a broadband source via monomode fibres. The path imbalance in the F–P 'sensor' was ±45 fringes ($69{\cdot}8\,\mu$m) for these measurements. The insert in the Figure emphasises the low-noise nature of the signal detected. As a constant electrical input power leads to an exponential temperature increase in the heating tubes, and heating and cooling time constants are not necessarily equal, a nonlinear scan could normally result. This was partially corrected for in Fig. 2 by manually varying the heating rates during the heating cycle. Clearly for a real system, a programmable temperature controller will be necessary. The total scan time for our measurement was ~10 s, although this may in future be reduced by increasing the drive power or by reducing the thermal capacity of the heater.

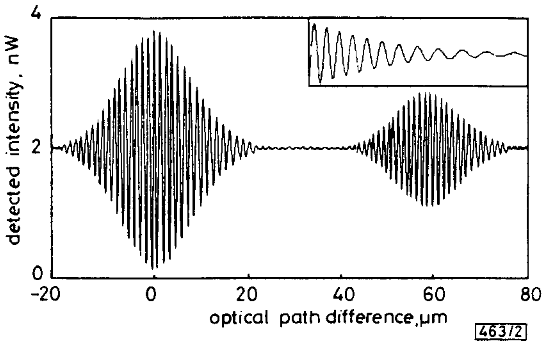

**Fig. 2** *Interference signal of readout interferometer for $\pm 95\,\mu m$ optical path difference*

A reproducible temperature scan could be used as an absolute measure of delay during the scan. However, for accurate systems ($\lambda/100$) we will require a better performance. This can be effected by detecting, simultaneously with the sensor interferogram, the interferogram of a locally injected laser source. With its longer coherence length, the latter will provide a continuous alternating reference signal as the delay is scanned. The laser should preferably be guided through the same fibre as that used for the sensor interferogram. (As a less desirable option, it could be guided in a separate fibre contained within the same heating tube.) Techniques are available to interpolate the phase of such a periodic reference signal to much better than $10^{-3}$ rad.

*Conclusion:* A new in-line fibre polarimetric interferometer for white light matched interferometry has been demonstrated. It may be constructed in a single spliced length of fibre, making for an optically-efficient and compact system. A differential scan of $\pm 180\,\mu$m was achieved with a scan time of less than 10 s, and used to match a remote Fabry–Perot etalon sensor. Future work will involve faster and more controlled thermo-optic modulation and simultaneous path difference calibration using a co-travelling narrowband source.

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# MICROWAVE OSCILLATOR PHASE NOISE REDUCTION USING NEGATIVE RESISTANCE COMPENSATION

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*Indexing terms: Noise, Oscillators, Microwave oscillators*

Two microwave oscillators at a free-running frequency of ~800 MHz are designed. Both were designed to have the same feedback factors; the difference lies in the output loading circuit. By using the inverted common collector (ICC) [1] configuration, a stable negative resistance is generated. This negative resistance is then used to compensate for the loss in the feedback path. Hence, a zero resistance loaded oscillator is implemented. A comparative study with experimental support confirmed that the zero loaded oscillator has a 6 dB and 18 dBc improvement in the phase noise and second harmonic rejection, respectively.

*Introduction:* The requirement of low phase noise in local oscillators has increasingly become a prime consideration in telecommunication systems design. The aim of this Letter is to report a novel way of designing low phase noise sources.

A standard model for the calculation of phase noise in oscillators is given by Leeson [2], based on feedback theory. According to the theory, four factors determine the oscillator noise spectrum, i.e. the noise figure, the loaded Q factor of the feedback loop, the noise corner frequency of the active device and the output power. In real design practice, only three factors can be controlled because the noise corner frequency is device dependent and is not readily available. The two oscillator designs reported in this Letter follow the complex terminal voltage–gain techniques described in Reference 3. To have a stable and pure signal output, the loaded Q factor of an oscillator should be as high as possible. In oscillator designs using lumped circuit elements, the most probable cause of Q-factor degradation in the feedback loop is the power consumed at the output (usually 50 Ω). By using nega-