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Thermally-Scanned, In-Line, Fibre Polarimetric Interrogator For "White-Light" Interferometry

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Abstract

A novel in-line fibre polarimetric interferometer for "white-light" matched interferometry is described. It consists of two equal lengths of polarization-maintaining fibre spliced with their polarization axes orthogonal. Differential temperature tuning scans the interferometer path difference by the free-space equivalent of $\pm 180\mu m$ to allow matching to a remote sensor interferometer.

1. Introduction and Principle of Operation

"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 phase 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 modulation ("channelled spectrum") on the initially smooth spectrum, the pitch of which characterizes the sensor's OPD. In a time-domain description of the effect, light beams propagating via the two paths of the interferometer are only correlated if the light in the shorter path is further delayed by a time $2d/v_g$, where v_g is the group velocity in the interferometer. If one chooses a value of d significantly larger than the correlation length of the broadband source, small variations in d will not cause visible interference fringes in the integrated signal.

If 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 instantaneous value of the scanned delay closely matches that of the remote delay. An independent measurement of the local delay allows determination 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).

In this paper we present a new method to construct a thermally-scanned polarimetric interferometer, using two nominally equal lengths of polarization-maintaining (PM) fibre, spliced together with their polarization axes at 90°. The arrangement is essentially that of the compensated polarimetric interferometer which has been used for differential sensing[5]. If not mechanically strained, the OPD between the two polarization 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 small-area detectors possible with this technique offer lower noise than self-scanned arrays.

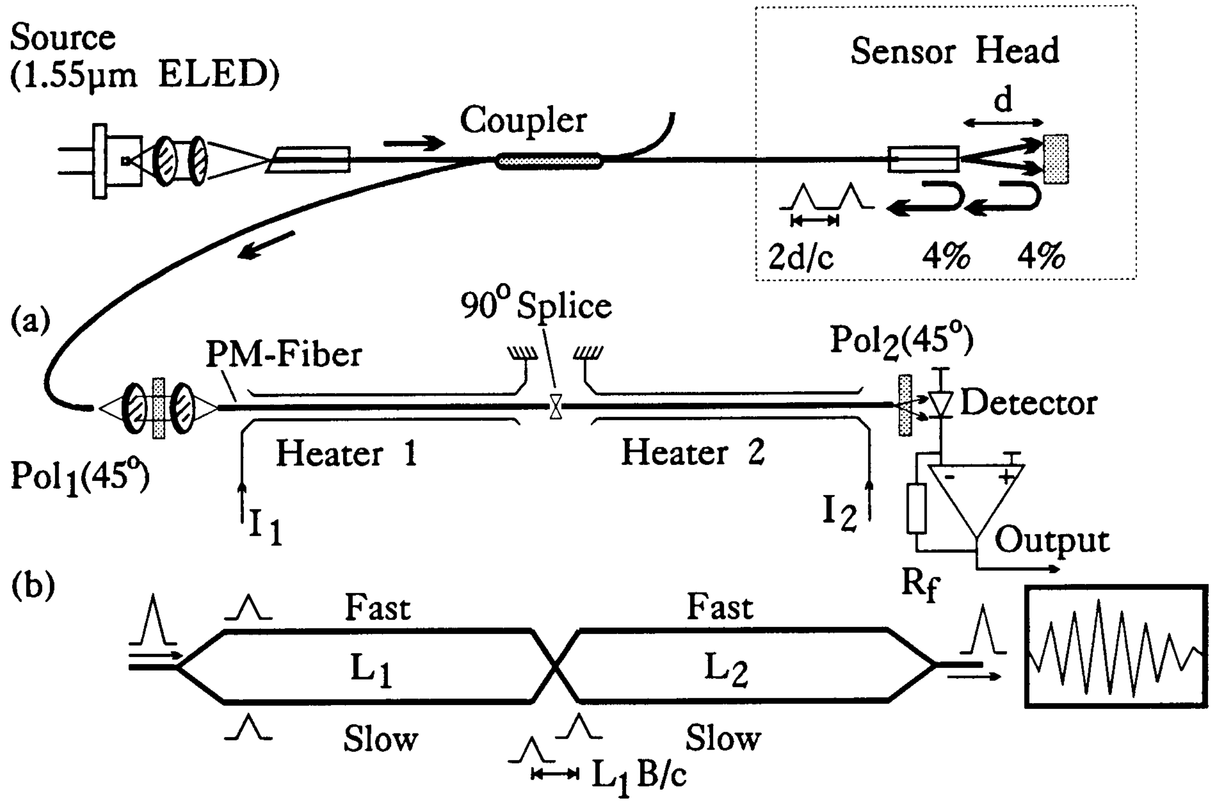

Fig.1(a) Schematic of thermally-scanned in-line fibre white-light matched interferometry. (b) illustration of fast and slow propagation paths in the 90°-spliced fibre lengths.

2. Experiment

Fig. 1 depicts the thermally-scanned, in-line, fibre WLI interrogation system. Light from a 1550nm fibre-pigtailed ELED, of $1/e^2$ bandwidth $\pm$42nm, is coupled, via a directional fibre coupler into a Fabry-Perot interferometer having a separation, d, to simulate a remote sensor. Power level at the sensor was 4μW. The Fabry-Perot cavity was formed between the end face of a singlemode fibre and a 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 of 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.

The receiving polarimetric interferometer was formed from two lengths (L_1=10097mm, L_2=10073mm) of PM-fibre (York Ltd. HB1550) with beat length 3.06mm. Equal optical power was launched into the fast and slow eigen-axes, 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=0.406mm, OD=0.635mm, resistance=25Ω), which could be heated by electrical current. By varying their temperature T_1,T_2, and hence the group indices of fast and slow modes, the total differential delay could be scanned through positive and negative values. A range of ±120 fringes (equivalent to a free-space OPD of ≈±180μm) was obtained for a temperature difference of 80°C. This is equivalent to mechanically scanning the mirror of a Michelson interrogation interferometer by ±180μm. Although the beams are CW, the relative delays are emphasized in Fig.1 by showing timing "markers".

The detected power transmitted through an analyser aligned at 45° to the eigen-axes was measured, as a function of the temperature difference, using a digital oscilloscope. The receiver consisted of an InGaAs photodiode and 500MΩ transimpedance amplifier. When the interferometer delays were closely matched, modulated fringe packets with a high signal-to-noise could be observed (Fig.2), despite the use of a broadband source via monomode fibres. The F-P sensor path-imbalance was ±45 fringes (69.8μm) for these measurements. The insert in the figure emphasizes the low-noise nature of the signal detected.

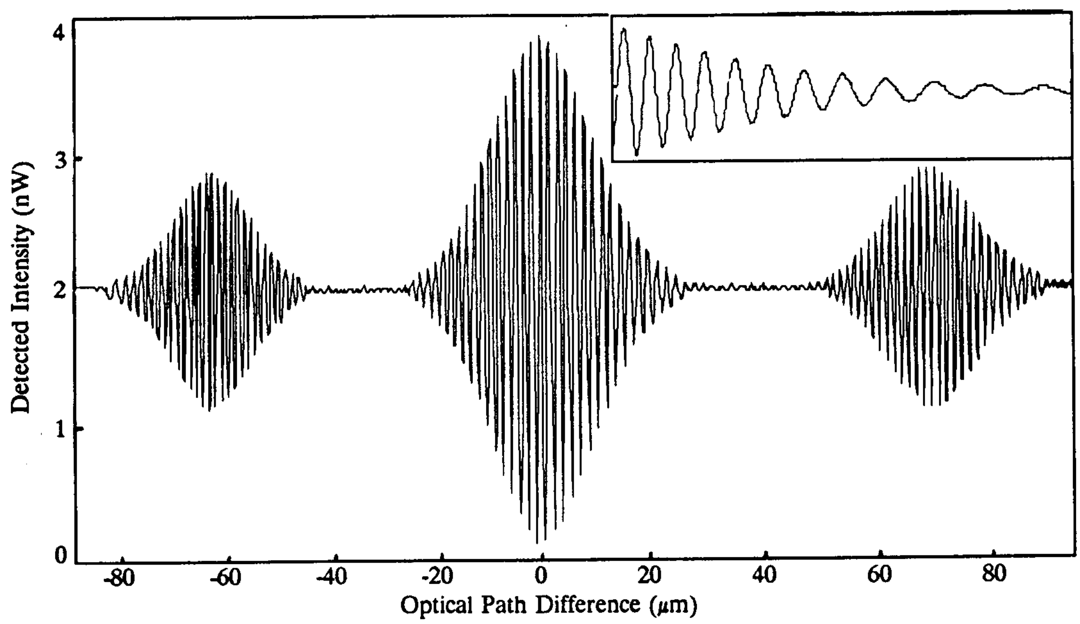

Fig.2 Interference signal of the readout interferometer for ±100μm optical path-difference.

3. 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 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 is reduced to:

$$D = \frac{L_1 B_1 - L_2 B_2}{n_{av}}$$

In our case, L_1 and L_2 were first matched to within 24±0.5mm, giving a mismatch of only 7 fringes when the fibres are of equal temperatures. 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.

Fig. 2 shows the interference fringes as a result of thermal scanning. 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 results. 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. Total scan time for the measurement is currently about 10s, although this can be reduced by increasing drive power or reducing the thermal capacity of the heater.

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 a 10^{-3} radian.

4. 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 10s, 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 narrow-band source.

5. Acknowledgement

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