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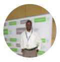

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Comparison of PMF and LEAF as Optical Fibre Stress and Temperature Sensing Elements

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Abstract: We experimentally investigate the sensitivity of PMF and LEAF fibre. The design of a stress sensor gave the best sensitivity of 0.051 kg^{-1} while that of a temperature sensor, gave the best sensitivity of 0.181 $^{0}C^{-1}$.

OCIS codes: (060.0060) Fibre optics and optical communications; (060.2370) Fibre optics sensors

1. Introduction

The field of measurement and instrumentation, particularly sensor development, is one that has expanded rapidly in recent years. The need for high quality sensors to be integrated into sophisticated measurement and control system is clear. In parallel with rapid advance in development of sensors based on microelectronics, those based on optical techniques have expanded significantly over last few years and have found many applications in the industrial field. This is because, compared with other types of sensors, fibre optic sensors have several advantages such as small size and weight, immunity to electromagnetic interferences, large bandwidth and hence offers possibility of high multiplexing potentials, intrinsically safe in explosive environments, highly reliable and secure with no risk of fire, high sensitivity and accuracy [1]. In spite of many advantages, there is a growing demand for improved sensitivity, reliability, accuracy, flexibility and better compatibility of fibre optic sensors for various applications. Fibre optic sensors can be used for the measurement of many physical or chemical properties [2]. The principle is based on the fact that light in an optical fibre can be modified in response to an external physical, chemical, biological, biomedical or similar influence. The technique used in this study is unique in terms of power saving. Others that have used pump-probe technique have applied high power.

2. Theory

Among the various optical sensor designs, polarimetric fibre optic sensor (PFOS) has its unique advantages over the rest [3]. When a force is applied along the length of a polarimetric fibre, an additional birefringence is introduced due to the elasto-optic effect i.e. the change in refractive index due to the applied force and is given by:

$$\Delta n = C_B F \tag{1}$$

where C_B is the Brewster constant and F is the applied force. In addition, in many cases, the stress or strain in different directions is different, so that the induced refractive index change is also different in different directions. Thus, there is an induced phase difference between different polarization directions. Under the external perturbation, such as stress or strain, the optical fibre works like a linear retarder. Therefore, by detecting the change in the output state of polarization (SOP), the external perturbation can be sensed [4]. The degree of polarization (DOP) as a measure of birefringence is given as [5]:

$$DOP = \sqrt{1 - \sin^2 \theta_S \left\{ 1 - \left[\left\langle \cos \Delta\psi(t) \right\rangle^2 \right] \right\}} \tag{2}$$

where $\Delta\psi(t)$ is the swing angle of the probe and θ is the angle between the probe and the pump. The angle θ_s can be obtained from θ and the pump- probe power ratio PR = (P_p/P_s) through the analytical relationship $\theta_s = \theta - \arctan((\sin\theta)/(PR+\cos\theta))$. The dependence of the DOP on the relative pump-probe polarization angle θ is implicit in θ_s. From (2) it can be concluded that, if polarization control of the signals ($\theta = \theta_s = 0$ or $\theta = \theta_s = \pi$) cannot be achieved due to polarization mode dispersion (PMD), the basic countermeasure against DOP degradation is to increase the bit walk-off by further spacing the channels or by using a more dispersive fibre.

3. Methodology

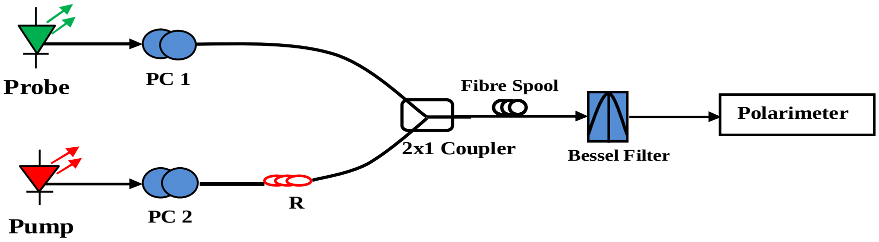

Fig. 1. Experimental set up: Fibre optic sensor design (PC ≡ polarization controller and R ≡ sensing fibre)

A linearly polarized probe of input wavelength 1552.52 nm and a similarly polarized pump at input wavelength 1552.92 nm, giving a channel spacing of 50 GHz (0.4 nm) both in the form of continuous waves, were coupled using a 2x1 coupler and co-propagated in a 1.7 km single mode fibre (SMF). The standard SMF had a linear PMD of $0.5\,\mathrm{ps}\sqrt{\mathrm{km}}$, effective area of 80 μm^2 and a dispersion parameter of 17 ps/nm-km. The probe and the pump signals were generated by a wavelength division multiplexing (WDM) source. Polarization controllers, PC1 and PC2 were used to set the input polarization angle between the pump and the probe SOPs at 90^0. An optical filter of bandwidth 0.3 nm was used to filter out the probe signal and a polarimeter was used to monitor the DOP of the probe.

For the design of a stress sensor, polarization maintaining fibre (PMF) and large effective area fibre (LEAF) were used as sensing elements. The sensor was optimized at different pump-probe power ratios PR, and at each value of PR, the pump channel at R-section in Fig 1. was subjected to varying weights within the range of 2.5-32.5 kg. The output probe DOP was then measured. The sensing length, 10.5 cm, was sandwiched between two thin transparent plastic sheets, so as to cover the sensor for protection against stress concentration. In temperature sensing, PMF and LEAF were also used as sensing fibres. The sensing length was immersed in a jar containing water that was heated to approximately 100 ^{0}C and allowed to cool. The cooling was not forced but exposed to the normal ambient conditions. A thermocouple was used to measure temperature, as the DOP of the probe was monitored with decrease in temperature.

4. Results and discussion

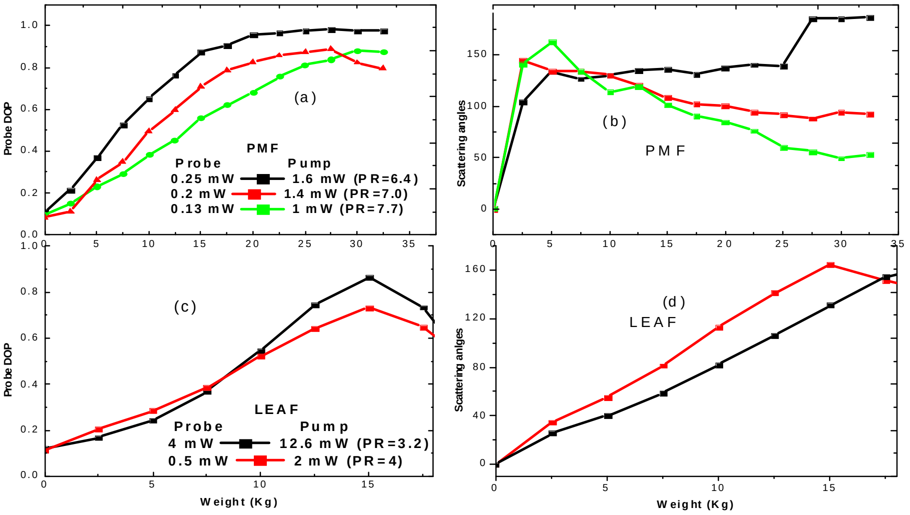

Fig. 2. Stress sensor using (a) polarization maintaining fibre (PMF) and (c) LEAF fibre. Corresponding scattering angles are given by (b) and (d).

From Fig. 2 (a) and (c), the DOP of the probe increases approximately linearly with increase in weight, up to 27.5 kg for PMF and 15 kg for LEAF. The weight applied at the sensing length along the pump channel introduces an additional birefringence according to Eq. (1). The induced birefringence rotates the SOPs of the pump, which in turn, linearly orientate those of the probe, hence, improved DOP. The sensor operates effectively up to a maximum critical weight of 27.5 kg for PMF and 15 kg for LEAF, beyond which the DOP tends to remain unchanged (black line for PMF), or drops (LEAF) with increasing weights as shown in Fig. 2 (a) and (c) respectively. This is because the polarization rotations of the pump has reached maximum, due to elasto-optic limit nature of the fibre.

As the pump-probe power ratio PR reduces, the sensitivity of the sensor increases. For PMF fibre (PR = 6.4) has higher sensitivity per unit weight of 0.051 kg^{-1}, followed by 0.045 kg^{-1} (PR = 7.0) and lastly, 0.034 kg^{-1} (PR = 7.7); while LEAF fibre (PR = 3.2) has sensitivity of 0.049 kg^{-1}, higher than that of 0.041 kg^{-1} (PR = 4). Reduction in PR leads to reduced Θ_s, according to the expression given in the paragraph below Eq. (2). When Θ_s is small, it reduces the value of the sine in Eq. (2) hence, improved sensitivity. It also, implies that the scattering on the probe signal has been minimized as depicted by Fig. 2 (b) and (d). For example, in Fig. 2 (b) (PMF) black line which has less PR is less scattered than green. Polarization maintaining fibre (PMF) covers a wider range of weights, than the large effective area fibre (LEAF). In LEAF, A_{eff} is normally increased intentionally, to reduce the impact of fibre nonlinearity. In other words, the LEAF fibre is a highly birefringent fibre thus; it reaches its elasto-optic limit much earlier.

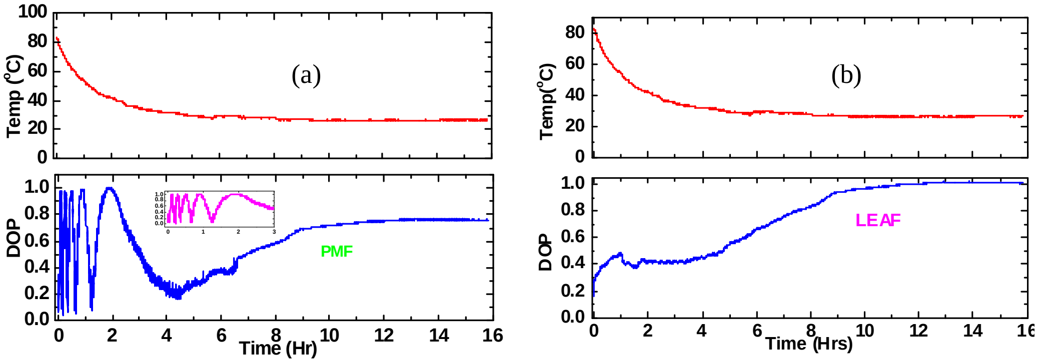

Fig. 3. Temperature sensor using (a) PMF (b) LEAF. Inset: A zoom of DOP the first 3 hours

Figure 3 (a) and (b) shows that the DOP of probe varies as a function of temperature. The rate or frequency at which the DOP varies for both PMF and LEAF at high temperatures is faster than at lower temperatures. Temperature-induced rotations reduce as the water cools, resulting in slower DOP variations as observed in Fig. 3 (a) and (b). Though, Fig. 3 (b) gives almost a linear graph for direct reading of DOP, the sinusoidal pattern in Fig. 3 (a) cannot be ignored completely because the repetition rate is consistent. The sensitivity for LEAF was 0.012 $^0C^{-1}$ while the average sensitivity for PMF was 0.181 $^0C^{-1}$ over a range of 30-90.9 ^0C.

5. Conclusion and recommendation

In summary, a sensor was designed according to its sensor requirements by selecting an appropriate type of fibre and by varying the relative pump-probe powers for sensor optimization. The simplicity of the design and low power requirements which results in the low cost of the fabrication is the point which makes it suitable for actual field application.

The pump-probe scheme uses only two channels; there is an open door for investigations for many inter-channel interactions but using the same principles as the ones employed in this study for possibility of other sensor designs. Also, in order to increase the sensitivity of the temperature sensor, it is recommended that a thermosensitive cladding of the fibre be used. Generally, fibre optic sensor technology offer unique possibilities in a measurement context and where this will lead depends particularly on the initiatives of the research community.

6. Acknowledgement

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