Optica Applicata, Vol. XXXVII, No. 1–2, 2007

Fibre optic pressure sensor and monitoring of structural defects

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Pressure induced microbends have been created in a 50 μm graded index multimode optical fibre with spatial periodicity $\Lambda = 4.5$ mm, embedded in the sample of araldite. If high pressure is applied directly to optical fibre having microbends, it may break, and if pressure is applied to embedded fibre in a solid structure without microbends, the sensitivity is lower. In this paper, a combination of the embedded sensor and microbend sensor is presented. It has the advantage of sensing high pressure on a structure with the sensitivity of a microbend sensor without breaking the optical fibre. It measures pressure up to 1.6 MPa with reproducibility within ± 5% of the measurand. The average sensitivity of the sensor is 5.3/MPa on an arbitrary scale.

Keywords: fibre, pressure sensor, microbend, structural defects.

1. Introduction

In recent years, investigations have been made concerning pressure sensors and health monitoring of structures [1–6]. In this area, there has been a need to develop a sensor to be used as a time monitoring device under cyclic loading conditions which may be employed for detection of dangerous strain levels in the structure and failure of materials as well. The concept of using optical fibres to sense the mechanical response of structure to the load applied has been implemented in the so called form of smart skins [7, 8]. An optical fibre embedded in a composite structure deforms together with the composite structure and modulates the light passing through the optical fibre when a physical parameter is changed in the surrounding environment. Work has been reported in the field of microbending sensors [9–12] and embedded sensors [13–18]. In this paper, a combination and advancement of both are put forward. Pressure induced periodic microbends have been created in the sample of epoxy matrix having optical fibre embedded in it [19–22]. In the present embedded microbend sensor, pressure is applied to the fibre through the intervening medium of epoxy matrix by making the fibre an integral part of the structure. Although a small portion of pressure applied to the sample is transmitted to the fibre, the deformation produced and hence the modulation incurred at the output is a measure of the total pressure applied to the sensing element. If we apply the total pressure directly to the fibre with microbending periodicity, the fibre may break. Thus, using a fibre embedded in the araldite matrix, we are able to sense high pressure without damaging the optical fibre.

2. Principle of sensor operation

Microbending is carried out by spatial variation in the layout of an optical fibre. This induces couplings between the modes of the fibre. Some of the couplings involve radiative modes. When a periodic microbend is induced along the fibre axis, light power is coupled between modes with propagation constants β_p and β_q satisfying [23–28]

$$\beta_p - \beta_q = \frac{2\pi}{\Lambda}$$

Here, Λ is the spatial frequency of microbends.

Power transfer will take place from the p-th to q-th mode. If the q-th mode happens to be a radiation mode, this transfer of power will result in a net transmission loss of the guided modes. Thus microbending produces loss. A microbending loss phenomenon is shown schematically in Fig. 1. On application of pressure the losses are enhanced. Hence, by monitoring the decrease in guided optical power across the core as a function of the amount of microbending induced on the fibre the pressure sensor may be fabricated.

Transmitted near field (TNF) technique is an index profile measurement technique of high spatial resolution. This technique essentially involves scanning measurement of intensity at the output end of a short length of multimode fibre [29, 30]. To get a core index profile there must not be any sharp bends along the length of the fibre. However, in the present sensor application, regular periodic microbends have been created in a small length of the fibre embedded in the sample and with variation in the pressure applied to the sample the strength of the scanned signal at the fibre end proportional to the output intensity has been measured.

3. Experimental details

Samples of araldite with 30% hardener and 10% aniline have been prepared with 50 μm graded index multimode optical fibre embedded in it. Ramp structure with spatial periodicity $\Lambda = 4.5$ mm has been created in the fibre during preparation, with the fibre inside the sample touching the ramps.

Experimental arrangement is shown in Fig. 2. Light is launched in the 50 μm parabolic index optical fibre by means of an incoherent source of light, a tungsten halogen lamp, through a 10× microscope objective. A magnified image of the fibre output end is projected onto the plane of an apertured photodetector driven by a stepper

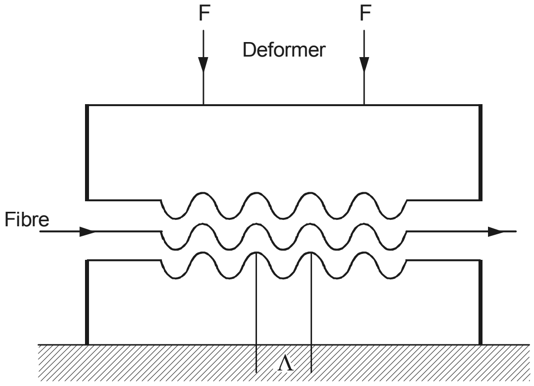

Fig. 1. Principle of microbending induced attenuation in an optical fibre.

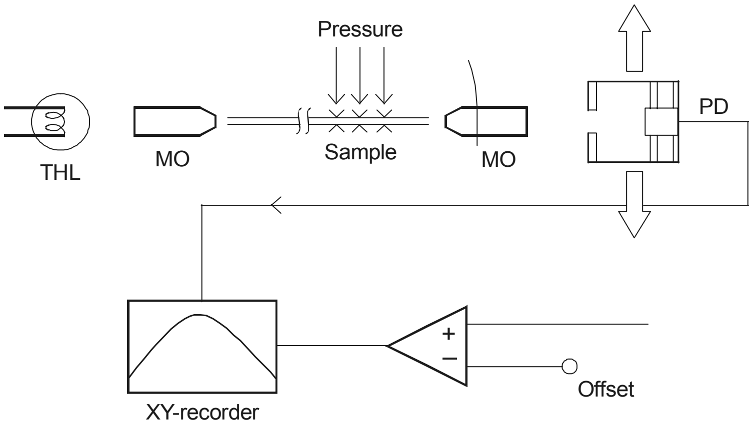

Fig. 2. Experimental arrangement (THL – tungsten halogen lamp, MO – microscope objective, PD – photodetector).

motor so as to scan the image along its diameter. The detector output, connected to a XY-recorder directly yields the near field intensity distribution as a near field profile. Here, the measurement of the intensity of the scanned signal has been done in terms of the peak value of the signal in arbitrary units. Pressure is applied to the sample by a hydraulic pressing machine and the output intensity is recorded as a function of pressure.

The experiment has been performed under laboratory conditions wherein the temperature has been maintained constant at 25 °C within ± 0.5 °C variation. It has been observed that loading and unloading does not yield any significant temperature change. Hence, the modulation in the output profile is only due to the change in pressure on the sample.

4. Results and discussion

Figure 3 (curve *a*) depicts a curve plotted on the arbitrary scale, for the intensity of the scanned output with an increase in pressure. The measurement of intensity here refers to the maximum value in the shape of the output profile and refers to a point measurement. With pressure increasing there is certainly more and more coupling observed between the cladding modes and higher order core modes. There will be power loss and the available power will decrease at the output end with increasing pressure, *i.e.*, the intensity of scanned profile should decrease with an increase in pressure. From the graph depicted in Fig. 3 (curve *a*), one can see that there is a consistent decrease in the intensity with pressure. The decrease in intensity initially for pressure up to 0.2 MPa is very high, *i.e.*, there is a fall of 40–45% in intensity for a pressure change of 0.2 MPa only. Subsequently, the decrease in intensity follows a gradually declining trend. However, it has not been possible to go beyond a pressure of 1.6 MPa, since beyond this pressure the fibre gets broken. Figure 3, curve *b* shows

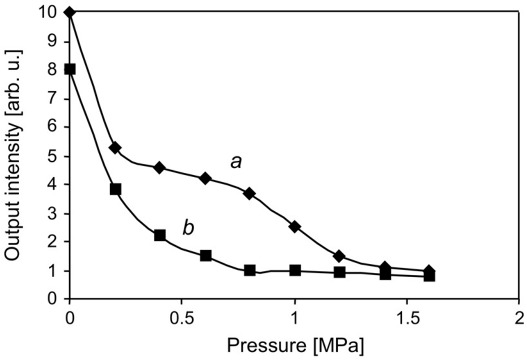

Fig. 3. Variation of output intensity with pressure increasing (*a*), pressure decreasing (*b*).

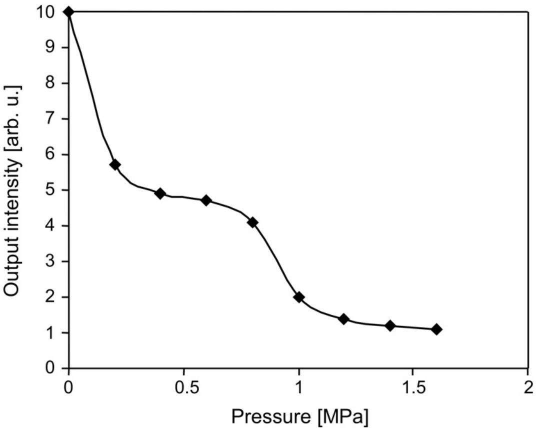

Fig. 4. Variation of output intensity with pressure (intermediate cycle).

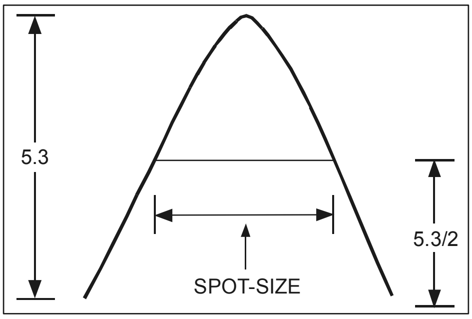

Fig. 5. TNF profile for a pressure of 0.2 MPa.

the case of the intensity of the scanned output measured on the same arbitrary scale when the pressure is decreased. Here we find less hysteresis in the higher pressure region, but in the region of 0.2 to 0.4 MPa of pressure, the hysterisis is high. The average hysteresis in initial cyclic operations is found to be nearly 13%. Many such cycles have been repeated to see the effect of cyclic operations. After a couple of cyclic operations the average hysteresis settles down to 5%. The experiment has been repeated over a period of time in order to check the effect of aging. The results have been found to be reproducible. Figure 4 shows pressure versus output intensity on an arbitrary scale for one such intermediate cycle after 72 hours. Here, too, we notice initially a large decrease in the intensity, then a gradually decreasing trend. Thus Figs. 3 and 4 show a regular change in the value of output intensity with increasing pressure. Sensitivity in the present scheme of things has been defined as the slope of the curve between the output intensity and the pressure. The slope has been calculated for different ranges of pressure and then the average has been taken to calculate the average sensitivity.

The spot-size of the scanned output profile has also been measured with an increase in pressure. Here, the spot-size is defined as the width of the output profile where the intensity of the profile falls down to half the maximum value. It has been found that the spot-size changes from 2.4 to 1.8 (on an arbitrary scale), when the pressure is increased from 0 to 0.2 MPa. The spot-size does not change on the application of additional pressure. The shape of the spot-size also does not change. Hence, it was not possible to calibrate pressure in terms of spot-size. The TNF profile for the pressure of 0.2 MPa is shown in Fig. 5.

Power launched in the optical fibre is shared by the core and cladding. With pressure increasing, the coupling takes place between the cladding modes and higher order core modes. However, the lower order modes are tightly concentrated in the core region with little penetration into the cladding region. In an optical fibre the effect of pressure is mainly confined to the plastic jacket and the cladding. There is little deformation of the silica core. Hence, if pressure is increased, the nature of the fundamental and other lower order modes changes very little and the spot-size does not change appreciably.

5. Conclusions

The monitoring of the structure would be possible by *in-situ* incorporation of the fibre at the time of making the structure itself. A regular decrease in the output intensity of light with pressure increasing in the embedded structure shows that the intensity modulated fibre optic pressure sensor described here can be used to continuously monitor the pressure up to 1.6 MPa under high pressure cyclic operation. It can be used to find out optimum/maximum pressure that the structure can withstand. Breakage of optical fibre in the course of increasing pressure to dangerous levels makes it an indicator of excess pressure in the structures. Upon breakage the output suddenly drops drastically and in the case of the araldite sample, light glows at the point where it has occurred. As the sample is semi-transparent, a precise spot of breakage in the fibre can be pointed out. The results found here show reproducibility. This sensor is robust, cost effective and reliable for measuring high pressure. It can be used to detect structural defects and for finding out maximum load that a structure can withstand. The average sensitivity of the sensor has been found to be 5.3/MPa, the reproducibility within ± 5% of the measurand and the maximum pressure measured is 1.6 MPa.

Acknowledgements – The authors are grateful to Prof. P.K.C. Pillai and Prof. T.C. Goel from Electret Laboratory, Department of Physics, Indian Institute of Technology, Delhi, for their useful suggestions.

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Received April 19, 2006
in revised form February 11, 2007