FIBRE OPTIC FORCE SENSOR AND ITS APPLICATIONS

P.P. Yupapin , S. Kusamran
Optoelectronics Research Laboratory, Department of Applied Physics, Faculty of Science,
King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand.
M. Hansupanusorn
Department of Physics, Faculty of Science, King Mongkut's Institute of Technology Thonburi,
Bangkok 10140, Thailand.

Abstract

An investigation of a fibre optic device configured as a fibre optic force or pressure sensor and its applications is carried out in this study. A length of sensing fibre, using polarisation maintaining fibre was employed as a sensing element, where the characteristic of the sensing fibre was studied. A light beam from a laser diode was launched into a sensing device via a delivery optical fibre and then the measurand signal was observed. Results of the sensing signals obtained were analysed by a basic Michelson interferometer, and the potential of using such devices for sensor applications is discussed. The feasibility of various force sensor applications is also discussed.

1. Introduction

Fibre optic sensors are recognized as attractive devices for measurement and control [1,2], offering a number of advantages, e.g., small size, light weight, and they can be used in high voltage, electrically noisy, high temperature environments, furthermore, they may be configured as remote sensing devices. Fibre optic sensors have been the subject of significant development because of these advantages. This study is concerned with the use of a Hi-Bi fibre in which force-induced cross-coupling of optical power within the fibre is allowed to occur [3,4], in response to externally applied environment. The magnitude of their changes may be adjusted and controlled relative to the output light intensity. To achieve this, light from a laser diode was linearly polarised and launched in one of the two eigenmodes of the Hi-Bi fibre employed[5]. The power coupled into the second eigenmode providing the required information on the applied environment of the coupling device.

This paper presents the basic principle of the fibre optic force sensor system and the experimental data for a force/pressure sensor and its applications. A novel and strategic investigation of the force sensor, using a highly birefringent fibre was carried out, as the basis of a new optical technique applicable to pressure monitoring. The performance of the system and aspects such as the optical method and the properties of the highly birefringent fibre were analysed in order to enhance instrument performance. Some applications of such a technique are as temperature sensor, aircraft sensors, medical sensors and multiplexed sensors.

2. Force Sensor System

When a beam of linearly polarised light is launched into one of the two eigenmodes of a Hi-Bi fibre, it normally remains in the same polarisation state. The output intensity with the polariser crossed will be a minimum, and will be a maximum when in a parallel position. When a force is applied to the fibre, a certain amount of optical energy may be transferred between the two polarisation modes. To achieve this, the coupling device consists of a pair of wedges each of width w, and the fibre is sandwiched between them. If the force is applied at the coupling point on the sensing fibre, as shown in figure l(a), then the coupling ratio, k, at that point can be related to the force, and this is given by [5]

$$k = G\,[\sin 2\varphi \sin(\pi B w/\lambda)]^2 f^2 \qquad (1)$$

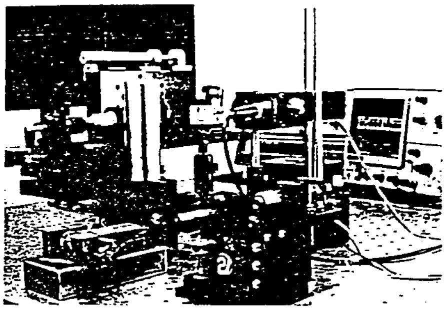
Here G is a constant, φ is the applied force angle between the direction of applied force and the fast axis of the fibre, B is the fibre birefringence, λ is the light source wavelength, w is the width of the coupling region (i.e. the coupling tooth width), and f is the force per unit length (i.e. F/w). From equation (1), the maximum coupling term can be obtained when the applied force angle is given by

$$\varphi = (2n+1)\,\pi/4 \qquad (2)$$

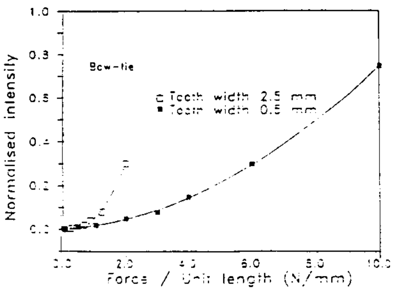
and the width of the coupling teeth,

$$w = (2n+1)L_B/2 \qquad (3)$$

where n=0,1,2,........., and L_B is the fibre beat length. This means that the first maximum of output intensity can be detected when $\varphi=45°$ and $w = L_B/2$. The other parameters in equation (1) can be arranged to be constant, and so the coupling ratio, and thus the coupled intensity will vary with the applied force, where the applied force angle (φ) was fixed throughout the experimental measurements. Thus, the required measurand may be obtained. Figure 1(b) shows the relationship between the optical normalised intensity and applied force, using two different teeth. The one using a tooth width of 2.5 mm obtained higher ouput intensity than the one having a footh width of 0.5 mm.



(a)



(b)

Figure 1(a). A fibre optic pressure sensor system. (b). A Graph of the relationship between force and output light intensity, using bow-tie fibre.

Further, the position of the coupling points along the fibre can be located when at least two coupling points are applied to it. One acts as a reference, and the position of the other may be found relative to it. The important property is that the distance between any pair of coupling points must be large enough for the optical path difference between the modes of the fibre to be outside the light source coherence length which is discussed in the next section.

3. Applications

In this section, the potential of using force sensor applications is discussed.

3.1 Position sensor

As shown in figure 2(a), a simple case where two coupling points are applied to the fibre may be considered and the optical path difference, OPD, is related to the fibre birefringence, B, by

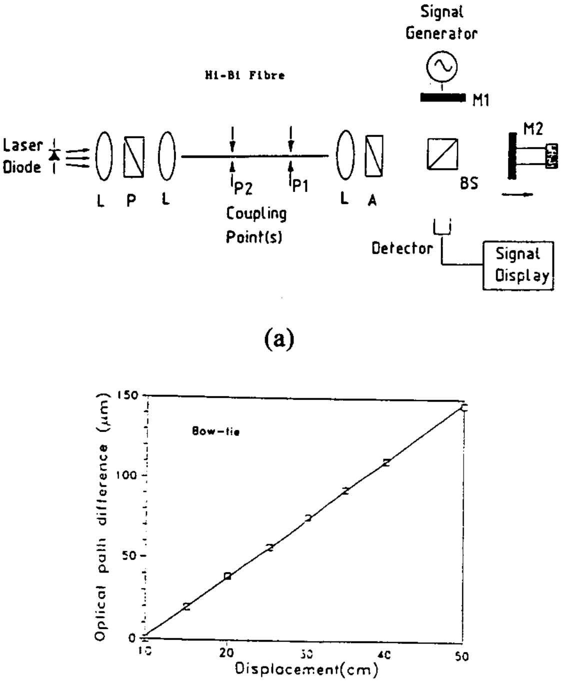
$$\mathrm{OPD} = B(L_r - L_i) \qquad (4)$$

where L_i and L_r are, respectively, the length of the fibre from the end of the fibre to the ith and reference coupling points. The interferometer output signals can then be detected, corresponding to this optical path difference by adjusting the position of one arm in the recovery interferometer, and thus the relation between the displacement along the fibre and the OPD in the Michelson interferometer matches that in the fibre, as given by equation (4).

This system can be used to locate many sensing elements distributed along the fibre in the same way, providing that the distances between their coupling points are arranged to be sufficiently large, so that their corresponding signal peaks will not overlap with each other in the output fringe visibility. This means that the separation between coupling points must be greater than the minimum separation distance, $(L_r-L_i)_{min}$, using equation (4), which can be expressed as

$$(L_r-L_i)_{min} = L_c/B \qquad (5)$$

where L_c is the coherence length of the optical light source. Figure 2(b) shows the linear relationship between OPD and displacement, where the position of coupling points along the fibre length is observed, i.e., as a position sensor. In this case, the sensor sensitivity of 2.63 μm/cm is noted.



(a)

(b)

Figure 2(a). Fibre optic position sensor system arrangement. (b). A Graph of the relationship between displacement and optical path difference, using bow-tie fibre.

3.2 Temperature sensor

For a Hi-Bi fibre, the relative phase retardation between the two perpendicularly polarised eigenmodes propagating in the fibre is given by

$$\Delta\varphi = (2\pi/\lambda))(\Delta nl) \qquad (6)$$

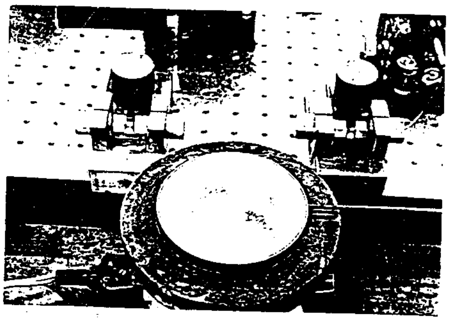
where l is the fibre length, Δn is the refractive index difference between the two eigenmodes, and the temperature-induced phase retardation can be expressed as[6]

$$d(\Delta\varphi)/dT = (2\pi/\lambda)\ [\Delta n(dl/dT)+\{d(\Delta n/dT)l\}] \qquad (7)$$

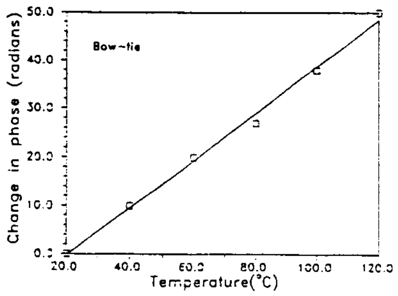
For example, using a light source with λ = 800 nm and bow-tie Hi-Bi fibre, i.e., fused silica fibre, n = 1.456, and $\Delta n = 4\text{x}10^{-4}$, $(l/l)\,(dl/dT) = 5.5\text{x}10^{-7}/\,^{\circ}\text{C}$, $d(\Delta n/dT) = 4.2\text{x}10^{-7}/\,^{\circ}\text{C}$, then

$$(1/l)[d(\Delta\varphi)/dT] = 3.30 \text{ radians}/^{\circ}\text{C.m} \qquad (8)$$

The effect of temperature variations on the coupled power may be investigated, using the system as shown in figure 3. Two coupling points are required to be reference points which applied to the sensing fibre, as this system has a very significant effect on the acceptability of the technique for sensor applications. The sensing fibre is placed in the temperature controlled environment and tested. The changes in OPD (i.e. phase) of the interference with respect to the reference signals are related to that of the environmental temperature. The result obtained from a bow-tie fibre shows a good linear relationship between temperature and light intensity, figure 3(b). A sensor sensitivity of 3.9 radian/° C. m is obtained.



(a)



(b)

Figure 3 (a). A temperature sensor system. (b). Graph of temperature sensor, using bow-tie fibre.

3.3 Robotic grip stress sensor

Figure 4 shows the experimental system and the measured variation in force and normalised intensity, where the force was applied to a sensing fibre as a force/pressure sensing element [7]. This reaction could then give rise to the relationship between the change of the applied force and output light intensity. The results obtained from the force sensor suggests the potential of using such a device for a robotic grip stress sensor.

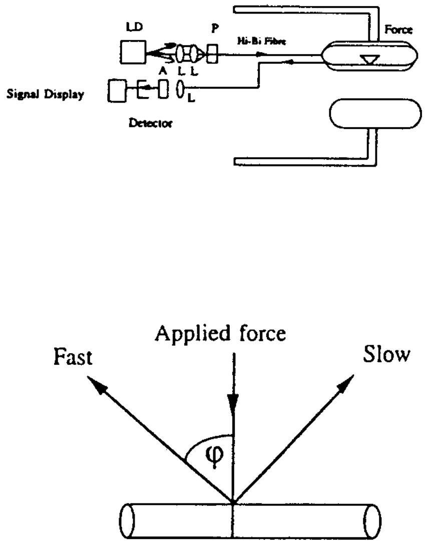


Figure 4. Illustration of robotic grip stress sensor system.

3.4 Flap angle measurement

The measurement of a dynamic change of flap angle can be carried out using a system as shown in figure 5 [8]. The direction of aircraft movement can be sensed more precisely, using a sensing fibre as a sensing element. In this case, the property of light intensity and force relationship may be investigated, then the direction of the aircraft may be sensed and controlled by using a fibre optic sensor system..

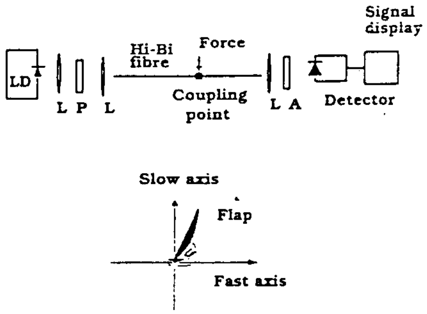


Figure 5. Illustration of a flap angle measurement system.

3.5 Pressure measurement

The apparatus used is as shown in figure 6 [9]. The change of pressure on the aircraft may be carried out using a fibre optic sensor system in the same way as with the flap angle measurement. The response of pressure may be easily detected and known during monitoring time.

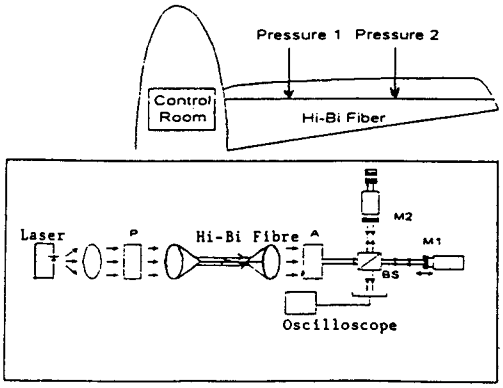


Figure 6 A. schematic diagram of an aircraft sensor system arrangement.

3.6 Medical sensors

The use of a simple optical fibre sensor employed as a medical sensor [10] is shown in figure 7. The potential of the instrument to measure a range of parameters through their interaction with the optical parameters of the force/pressure sensor is proposed. One possible application is a respiration sensor which is responsive to fluctuations in breathing. Such a device is convenient to use during the sleeping period where it may be used to monitor breathing throughout the period. Furthermore, it may be applied and linked to networks for remote sensing, using just a single control system.

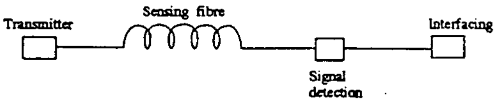


Figure 7. Illustration of a fibre optic medical sensor system arrangement.

3.7 Multiplexed sensors

One major application of such technique in sensing will be optical multiplexed sensors [11], where the schematic diagram of a sensor system is as shown in figure 8. The changes that occur due to the effects of the environment may be sensed using the sensor head based on the fibre optic device. Clearly it will be necessary to ensure relatively constant temperature and humidity, etc., conditions. This aspect is the subject of further study submarine sensor, environmental sensor and industrial applications, where a variety of parameters may be observed and controlled.

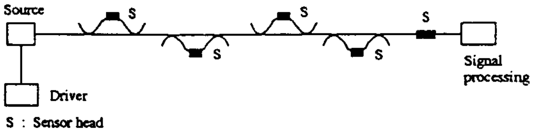


Figure 8. Illustration of a multiplexed sensor system.

4. Conclusion

The major objective of the work undertaken was the investigation, development and application in the laboratory context of the optical methods for a force sensor, especially for the investigation of changes occurring in the fibre optic sensor. Such systems build upon the developments in recent year in optoelectronics and optical fibres, and are coupled with the increasing interest in fibre optic sensors and their applications. The economic importance of such work is clearly seen by the degree to which international investment has been placed in the field and the extent to which these problems and their solutions are seen.

In applications, a series of "multiplexed" fibre optic sensors for measuring mode conversion (coupled power) along polarisation-maintaining fibre have been discussed. Mode coupling effects in the Hi-Bi fibre having different birefringence and structures have been studied using an interferometric method. The sensors may be used to measure force-induced coupling power of the fibre employed which may be observed using an interferometer, and with a specially designed optical fiber sensing unit. By means of this method, the magnitudes and locations of mode coupling caused by transverse force/pressure, temperature or position may be evaluated quantitatively.

5. Acknowledgements

The authors are pleased to acknowledge the support from National Electronics and Computer Technology Centre(NECTEC) for this work.

6. References

[1] Giallorenzi,T.G.,J.A.Bucaro,A.Dandridge, G.H. Sigel, JR., J.H. Cole, S.C. Rashleigh and R.G. Priest. 1982. Optical fibre sensor technology. Quantum Electronics 18 : 629-665.

[2] Udd, E. 1991. Fibre Optic Sensors: An Introduction for Engineers and Scientists. John Wiley & Sons Inc., New York.

[3] Noda,J., K. Okamoto, and Y. Sasaki.1986. Polarisation-maintaining fibres and their applications. J. Lightwave Technology 4 : 1071-1089.

[4] Tsai, K.H., K.S. Kim, and T.F. Morse. 1991. General solutions for stress-induced polarisation in optical fibres. J. Lightwave Technology 9 :7-17.

[5] Yupapin, P.V.P., K. Weir, K.T.V. Grattan and A.W. Palmer. 1995. A study of polariszation maintaining fibre characteristics with applications to force and displacement sensing. J. Laser Applications 7: 89-97.

[6] Yupapin, P.V.P., K. Weir, K.T.V. Grattan and A. W. Palmer. 1993. A polarimetric interferometry based pressure sensor for qualitative measurements. J. Flow Measurement and Instrumentation 4 : 145-149.

[7] Kusamran, S. and P.V.P. Yupapin. 1994. A robotic grip stress fibre optic sensor. Proc. 2nd Int. Symposium on Measurement Technology and Intelligent Instruments(ISMT II' 93). Wuhan, SPIE 2101: 874-91.

[8] Yupapin, P.V.P., K. Weir, K.T.V. Grattan and S. Kusamran. 1993. A flap angle control based fibre optical measurements. Proc. Sensors and their Applications VI Conference, Manchester : 323-328.

[9] Harnsupanusorn, M., P.V.P. Yupapin and W. Ngamaramvarangkul. 1995. Fibre optic aircraft sensor 21st SST : 646-647.

[10] Chunpeng, P., P. Sukrong and P.P. Yupapin. 1995. Fibre optic respiration sensor. KMITL 3: 37-39.

[11] Harnsupanusorn, M., P.V.P. Yupapin, S. Kusamran and S. Akavipat. 1993. Fibre optic multiplexed sensors. Proc. 5th NECTEC Conference : 153-159.