A NOVEL HOLLOW-GLASS MICROSPHERE SENSOR FOR MONITORING HIGH HYDROSTATIC PRESSURE

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ABSTRACT

Laboratory prototypes of a novel pressure sensor have been produced using a hollow glass microsphere, bonded, in an on-axis position, to the end of a monomode optical fibre. The sphere surfaces form a low finesse Fabry-Perot interferometer. The construction of the probe is simple in concept, yet the sensing element is intrinsically hermetically sealed. Experimental trials, under the influence of hydraulic pressure have been carried out and show a good match with predicted behaviour. The observed shift in wavelength with pressure was -0.93 nm/MPa, two orders of magnitude higher than that we have measured with a in-fibre-grating sensor under similar conditions. The ratio of the pressure sensitivity to the temperature sensitivity for our microsphere sensor was more than two orders of magnitude better than the in-fibre-grating type, so therefore less compensation is necessary to correct for temperature changes. This new form of sensing probe has potential for many high-pressure sensing applications.

1. INTRODUCTION

Fabry-Perot (F-P) sensors have been reported for the measurement of strain, temperature, pressure, vibration and acoustic waves[1,2]. Several methods of creating extrinsic fibre-optic F-P interferometers have been described[3-5]. Fairly sophisticated separation methods are required in the probe head to maintain the mirror spacing, yet allow the sensor to be sealed against ingress of foreign material. In our method a hollow glass microsphere is bonded, in an on-axis position, to the end of a monomode optical fibre. A low finesse F-P cavity is then formed between the sphere surfaces. The main advantages of our new arrangement is that the probe is simple, miniature and hermetically sealed. As with earlier F-P sensors[3-5], the probe is conveniently addressed by monitoring its reflection spectrum. The wavelength of each peak reflection and the span between peaks are both dependent on the physical spacing between the reflective surfaces.

2. SENSOR CONSTRUCTION

A schematic of the sensor construction is shown in Fig.1. Light from a 1550 nm fibre-pigtailed ELED is coupled into the sensor head via a directional fibre coupler. The sensing probe was tested within a cavity in a high pressure vessel, hydraulic pressure being applied to compress the sphere. The reflectance of the probe was monitored using a commercial optical spectrum analyser (ANDO AQ-6310B), located to receive light from a return port of the coupler. Reflections from the unused output port of the coupler were suppressed using index-matching oil. The hydraulic pressure system consisted of a hydraulic pump, a commercial precision pressure transmitter (Druck PDCR 960) and a purpose-designed pressure vessel capable of being used up to 70 MPa.

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3. THEORY OF THE F-P SENSOR

The observed F-P interference occurs between light reflected from the spherical surfaces of the glass bubble sensing element. Only the first reflections from each inner surface of the sphere were significant in our sensor as, firstly, the reflection was low at each surface and, secondly, the outer surfaces of the sphere were matched by bonding cement. As a result, the interference can be considered to be essentially two-wave interference only. The observed intensity, I_D, at the optical spectrum analyser is then a result of coherent superposition of light arising from reflections at each inner surface of the hollow glass sphere. I_D is given by:

$$I_D = k[A_1^2 + A_2^2 + 2A_1A_2\cos(\frac{2\pi}{\lambda}2d)] \tag{1}$$

where k is a constant, A_1 and A_2 represent the electric field amplitudes of the interfering light from the two surfaces of the sphere, λ is the wavelength of the source, and d is the spacing within the F-P cavity (ie. d is the inner diameter of the sphere). The free spectral range (FSR) of the F-P resonant cavity is given by:

$$FSR = \frac{c}{2d} \tag{2}$$

Where c is the free-space velocity of the light. Maxima in the reflectance spectrum occur when:

$$\lambda = \frac{2d}{m} \tag{3}$$

where m is an integer. By differentiating equation (3), and substituting for m, the change in wavelength of peak reflection, $\Delta\lambda$, resulting from a change in pressure, ΔP, is given by:

$$\Delta\lambda = \frac{\lambda}{d}\frac{\delta d}{\delta P}\Delta P \tag{4}$$

The effect of isotropic pressure on a perfect hollow sphere would normally be to cause only a compressive load on the material and reduce its diameter. A perfect sphere should therefore be capable of withstanding enormous pressure. In practice, however, an imperfect sphere, or one which is bonded to an external body on one side, as ours was, will suffer asymmetrical compression and will hence collapse at high pressure. We shall assume, for the present, in our analysis, that the sphere is perfect and that the pressure is isotropically applied. The induced strain, Δd, in a hollow sphere, exposed to a isotropic external pressure, P, can be expressed as[6]:

$$\Delta d = -\frac{Pd^2(1-\nu)}{4Yt} \tag{5}$$

where t is the wall thickness of the sphere, and Y and ν are the Young's modulus and Poisson's ratio of the material of the sphere, respectively. From eqn. (4) and (5), we obtain the response of the sensor in terms of the pressure-induced fringe shift:

$$\Delta\lambda = -\frac{\lambda d(1-\nu)}{4Yt}\Delta P \qquad (6)$$

This relationship shows that, as expected, the sensitivity to pressure can be increased by choosing a larger diameter sphere, provided the wall thickness remains the same. The most suitable wavelength to choose for monitoring of the fringe-shift will depend on the spectral response of the source. The expected cross-sensitivity to a change in temperature, ΔT, is given by:

$$\Delta\lambda = \frac{\lambda}{d}\frac{\delta d}{\delta T}\Delta T \qquad (7)$$

4. RESULTS AND DISCUSSION

Figure 2 shows the reflected spectrum, observed in the wavelength domain, with a sensing probe fitted with a 120 μm diameter sphere of approximately 0.8μm wall thickness. This spectrum shows a fringe spacing of 10 nm, as expected from eqn. (2). The maximum intensity contrast of the fringes between peaks and minima of the reflected spectrum was 3.8 dB. The pressure response of the sensor is shown in Fig. 3. This shows the variation of the wavelength of a particular reflection maximum (chosen to be 1552.47 nm at zero pressure) with pressure. The mechanical compliance of a hollow sphere is much higher than that of a solid body, such as a fibre or an in-fibre grating, so the fractional shift in wavelength with pressure is naturally much higher. From eqn.(6), we would have expected a pressure response of -0.83 nm/MPa, whereas our measured gradient was -0.93 nm/MPa. Uncertainties in the wall thickness of the sphere and our lack of knowledge of the precise value for Young's modulus for the material of our sphere are the most likely reason for the discrepancy.

The hollow-glass spheres used in our experiment are made from C-glass (soda-lime-borosilicate). We were unfortunately unable to obtain precise information on the material used, so we have assumed a typical Young's modulus value of 7×10^{10} N/m^2 and a Poisson's ratio value of 0.2, typical for C-glass, in order to perform our sensitivity calculation. As we mentioned earlier, a perfect sphere should withstand enormous isotropic pressure. Our sphere is bonded on one side to the optical fibre, so we expected it to implode eventually. In our first trials we deliberately tested the sensor up to the implosion point. The observed implosion pressure for spheres in our experiment was typically above 7 MPa. This should be adequate for many applications. For higher pressure measurement, a smaller or thicker-walled sphere could be used. A particular advantage of this new sensor is that the wavelength shift observed in our experiment was two orders of magnitude higher than that we have recently measured with a in-fibre-grating pressure sensor[7]. Of course, the pressure sensitivity could be increased further by choosing a larger sphere of the same wall thickness, but this would be likely to lead to a lower implosion limit.

Measurements of the cross-sensitivity to temperature of our sensing probe, shown in Fig.4, indicate that the errors due to temperature changes are relatively small. The measured temperature coefficient of wavelength variation was 0.0077 nm/°C. In particular, the ratio of the responses of the glass bubble to pressure and temperature were over two orders of magnitude better than we observed for the in-fibre-grating sensor.

5. CONCLUSIONS

A novel fibre optic sensor for monitoring hydrostatic pressure has been constructed. The sensor head is extremely small, the construction is simple and the sensing element has intrinsic hermetic sealing. A fringe displacement of 5.8 nm at 6.3 MPa pressure was observed. The sensitivity is two orders of magnitude higher than we have measured with a in-fibre-grating pressure sensor, and the relative effects of cross-sensitivity to temperature are much less.

6. ACKNOWLEDGMENT

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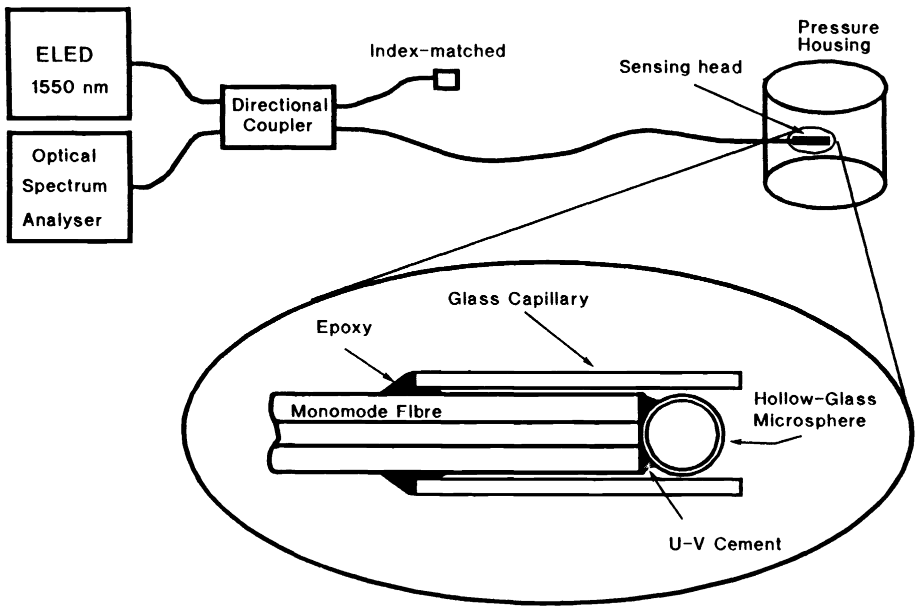

Fig 1. Schematic of the hollow-glass microsphere pressure sensor

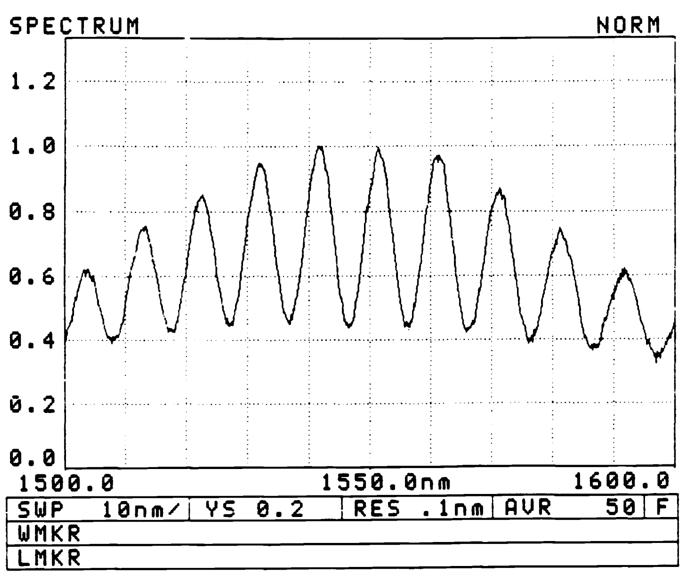

Fig.2 Reflected spectrum from sensing probe

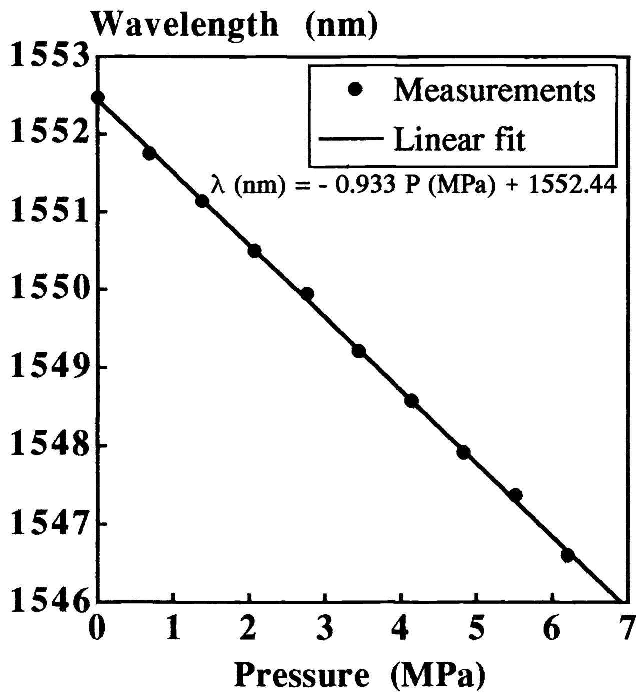

Fig.3 Pressure response of the sensor

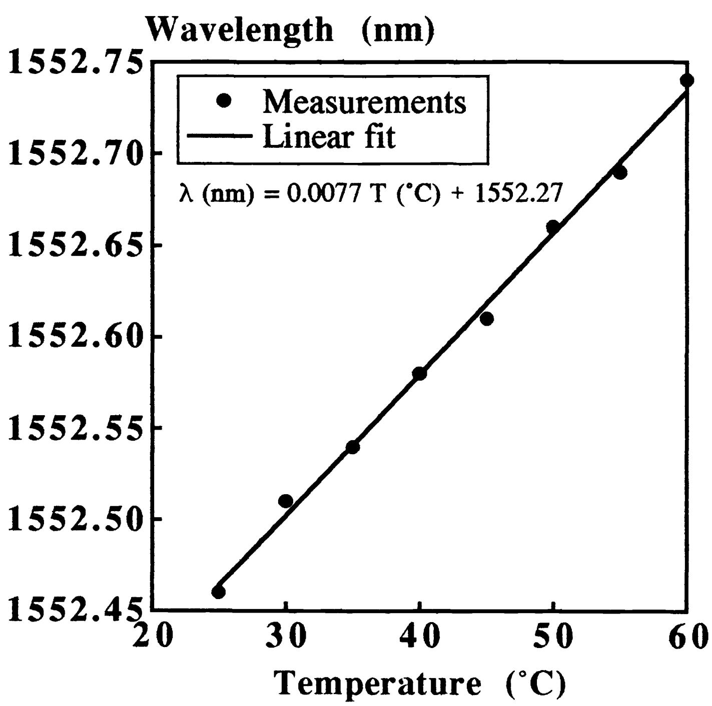

Fig.4 Temperature response of the sensor