A novel fibre optic sensor probe with enhanced sensitivity

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A novel fibre optic sensor (FOS) probe with enhanced sensitivity is proposed here. The sensing principle is based on double pass evanescent field absorption from an unclad U-shaped region of a multimode optical fibre which has occurred due retro-reflection of propagating light signal from an angle-shaped fibre tip. The sensitivity of the proposed sensor has been compared with a single-pass evanescent field absorption FOS.

Keywords: Back reflectance, evanescent field absorption, fibre optic sensor, light signal.

FIBRE optic sensor (FOS) based on evanescent field absorption from a side polished or unclad U-shaped optical fibres has been widely studied in recent years[1–6]. In a U-shaped FOS, enhanced penetration of the evanescent field to the external surrounding medium has been exploited for sensing investigation[7]. Because of the bending region, the U-shaped FOS can be used as a probe for sensing of various parameters of interest. With an unclad U-shaped optical fibre probe, one can achieve higher sensitivity than that of a tapered or straight unclad fibre-sensing region[8]. Again, FOS using one end of the fibre as a sensing region has been studied for measurement of different parameters in the recent past[9–12]. For such sensors, one end of the fibre is polished to form an angle-shaped tip[10] or a hemispherical-shaped tip[12], and other end is flat-polished. The angled or the hemispherical-shaped fibre tip is the key region for sensing investigation in this class of sensor. Light signal propagating from flat end of the fibre is reflected back at the fibre tip–air interface[10] by total internal reflection. As the sensing tip is brought into intimate contact with a medium of different index of refraction, the condition for total internal reflection is modified and thus modulates the back-reflected light signal. The sensing arrangement shows step-variation to the modulated signal.

Combining the above two sensing schemes, we present a novel FOS with double-pass evanescent field absorption from an unclad U-shaped multimode optical fibre. This is the sensing region for the present sensor. One end of the fibre is polished to form an angled tip, so that propagation of modulated light signal is back-reflected at the fibre tip–air interface by the effect of total internal reflection. The back-reflectance light signal from the fibre tip further undergoes modulation in the bending region of the fibre, thus enhancing the sensitivity of the sensor. The advantages of the technique are its simplicity and a cost-efficient approach to design a highly sensitive FOS.

In a typical step-index multimode optical fibre, one end is polished to form an angled tip, whereas the other end is flat-polished. Now, if light signal is introduced from the flat end, then the forward-going modes will be reflected back from the fibre tip–air interface. The critical angle condition for the back-reflected mode is given by[9] the following equation

$$\theta_c(\lambda) = \arcsin[n_a(\lambda)/n_1(\lambda)], \quad (1)$$

where $n_a(\lambda)$ is the refractive index of air and $n_1(\lambda)$ the index of refraction of the fibre core. Now, if the central part of the fibre is uncladded and made to form a U-shaped probe as shown in Figure 1, then there will be evanescent field absorption at the bending region. If θ represents the angle that a guided ray makes with the normal to the core–cladding interface in the straight fibre, this angle is transformed to angles φ and δ at the outer and inner surface of the bending region respectively. Thus, evanescent field absorption at the outer surface of the shaped core is given by[8,13] the following

$$\gamma_1(\text{outer}) = \alpha\lambda n_1/2[2\pi\rho(NA)^2]$$

$$\times \int_0^{2\rho}\int_{\varphi_1}^{\varphi_2} \frac{\cos^3\theta \, \mathrm{d}\theta \mathrm{d}h}{(1-n_1^2\cos^2\theta)^2(n_{12}^2\sin^2\theta-1)^{1/2}}$$

$$\div \int_0^{2\rho}\int_{\varphi_1}^{\varphi_2} \frac{\sin\theta\cos\theta \, \mathrm{d}\theta \mathrm{d}h}{(1-n_1^2\cos^2\theta)^2}, \quad (2)$$

with integral of $\mathrm{d}\theta$ ranging from φ_1 to φ_2 for the outer surface, where

$$\varphi_1 = \sin^{-1}\frac{[(R+h)n_{c1}]}{[(R+2\rho)n_1]}, \quad (3)$$

and

$$\varphi_2 = \sin^{-1}\frac{(R+h)}{(R+2\rho)}. \quad (4)$$

Similarly, the evanescent field absorption coefficient for the inner surface of the sensing region is given by

$$\gamma_2(\text{inner}) = \alpha\lambda n_1/2[2\pi\rho(NA)^2]$$

$$\times \int_0^{2\rho}\int_{\delta_1}^{\delta_2} \frac{\cos^3\theta \, \mathrm{d}\theta \mathrm{d}h}{(1-n_1^2\cos^2\theta)^2(n_{12}^2\sin^2\theta-1)^{1/2}}$$

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$$\div \int_0^{2\rho} \int_{\delta_1}^{\delta_2} \frac{\sin\theta\cos\theta\, d\theta dh}{(1-n_1^2\cos^2\theta)^2}, \quad (5)$$

where integral of $d\theta$ is ranging from δ_1 to δ_2, and

$$\delta_1 = \sin^{-1}\frac{(R+h)n_{c1}}{Rn_1}, \quad (6)$$

$$\delta_2 = \frac{\pi}{2}. \quad (7)$$

Thus, the total effective evanescent absorption coefficient in the case of a U-shaped sensing region is given by

$$\gamma(\text{effective}) = \gamma_1(\text{outer}) + \gamma_2(\text{inner}). \quad (8)$$

In eqs (2) and (5), h is the height at which the ray is incident on the entrance of the sensor from the core–cladding boundary, ρ the core radius and R the bending radius of the fibre. λ is the operational wavelength of the light source and α represents the bulk absorption coefficient of the surrounding medium. In practice, absorption of evanescent field takes place from the outer surface of the U-shaped region and contribution from the inner surface is insignificant. Hence, we can ignore eq. (5).

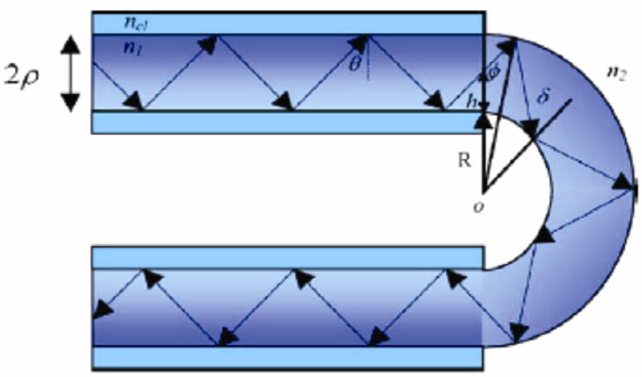

Figure 1. Geometry of a U-shaped sensing region and representation of a meridional ray in it.

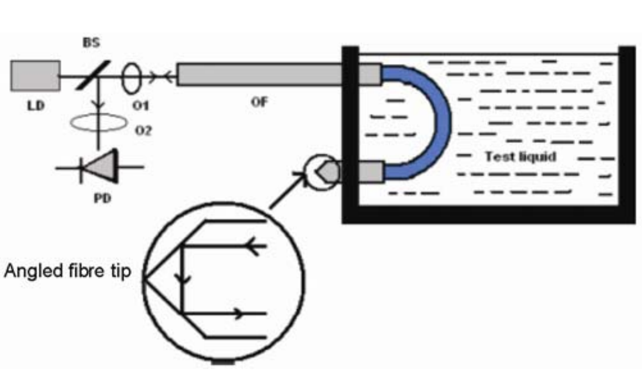

Figure 2. The experimental arrangement for the present fibre optic sensor. LD, Laser diode; BS, Beam splitter; O1, Objective; O2, Objective; OF, Optical fibre, and PD, Photodiode.

Forward-going modulated light signal is back-reflected from the fibre tip–air interface to the entry port by total internal reflection. Thus the modulated light signal undergoes further absorption at the bending region. Therefore, this arrangement provides higher sensitivity than that of a single-pass evanescent field absorption sensor.

The simple experimental arrangement for the present sensing investigation is shown in Figure 2. A laser diode with emission wavelength of 670 nm and output power of 5 mW is coupled to the flat end of the fibre through an objective. The evanescent field of the forward-going modes interacts with the surrounding medium in the bending region of the fibre and is back reflected at the fibre tip–air interface. The back-reflectance modulated signal further undergoes absorption at the bending region and is finally received by the photo detector (photodiode). For different refractive index medium in the surrounding region of the U-shaped fibre probe, we choose propylene glycol as a test sample. Its index of refraction can be varied by adding pure water into it. Several samples of different refractive indices have been prepared, and indices of refraction of all the samples were measured using Abbe's refractometer.

Prior to studying the sensor response for double-pass evanescent field absorption, sensor response for single-pass absorption was studied with a same length, core diameter, numerical aperture and equal bending radius of 2.5 mm optical fibre. In this case, the detector was placed at the second end port of the fibre.

Figure 3 shows the comparative response of the proposed sensor for single-pass and double-pass evanescent

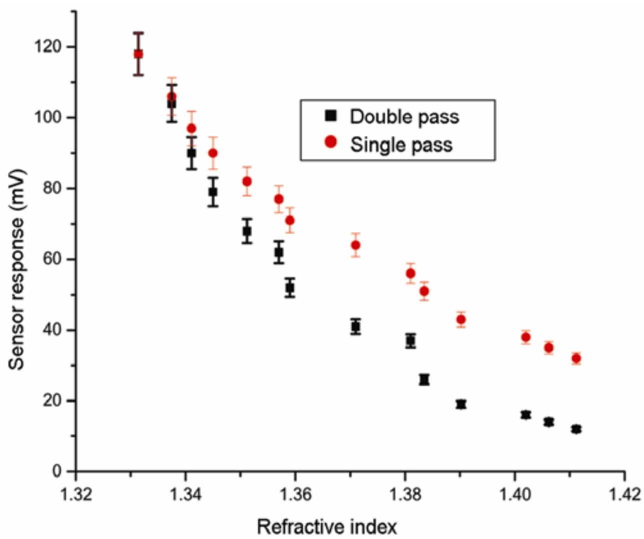

Figure 3. Sensor response for single pass and double pass evanescent field absorption.

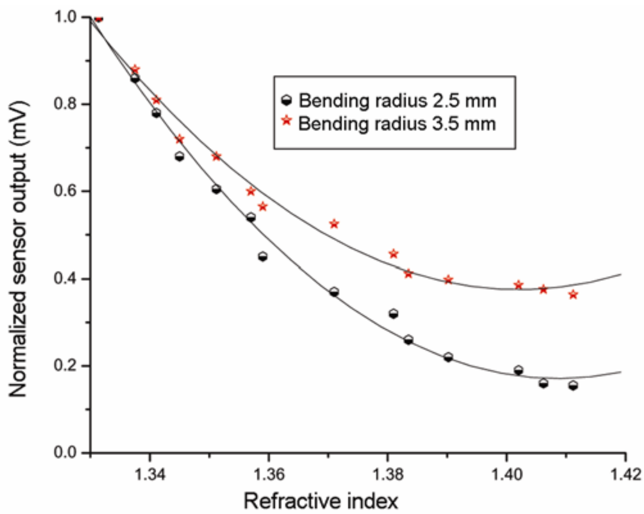

Figure 4. Normalized sensor response for different bending radii.

field absorption at the fibre sensing region. These responses clearly indicate that with double-pass evanescent field absorption, the sensitivity of the sensor (i.e. the change in modulated light signal with unit change in index of refraction of the surrounding medium) is higher than that of a single-pass absorption sensor.

The response of the sensor has been studied for different bending radius of the sensing region. Figure 4 depicts the sensor responses for fibre probes with two bending radii, 3.5 and 2.5 mm radius of curvature. It can be seen from these responses that with decreasing bending radius of the U-shaped probe, higher penetration of the evanescent field to the surrounding medium would take place, thus showing higher sensitivity[7]. Again, from eq. (2), it is also evident that with decreasing bending radius of the fibre sensing region, the evanescent absorption coefficient increases, thus yielding higher sensitivity. In the present work, double-pass evanescent field absorption of the sensor has been studied with only angle-shaped (porroprism) fibre tip. There is, however, further scope for studying the sensitivity of the present sensor with retro reflecting fibre tip[9]. The present FOS may be useful for developing other highly sensitive sensors.

A technique that yields enhanced sensitivity in FOS is presented here. The sensor principle is based on double-pass evanescent field absorption from the sensing region. The advantage of the technique is that both light signal input and modulated light output are through the input port of the fibre; thus, the sensing scheme can be used as a probe-like arrangement. Also, a small length of the fibre (15–20 cm) is sufficient to study the response of the present technique. The sensitivity of the sensor can be further enhanced by decreasing the bending radius of the fibre. The present technique may be useful in monitoring various physical and chemical parameters, such as temperature, relative humidity, chemical concentration (pH), etc. simply by coating suitable sensing chemicals on the surface of the sensing region of the fibre.

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