Fiber optic evanescent field absorption sensor with high sensitivity and linear dynamic range

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Abstract

A novel fiber optic evanescent field absorption sensor having high sensitivity and linear dynamic range is proposed. High sensitivity is achieved by using a U-shaped probe while linear response is obtained by preventing surface reactivity of the silica core of the fiber with the solute molecules of the absorbing fluid. To prevent it, a thin film of a suitable polymer is developed on the bare core U-shaped probe. A good degree of reproducibility of the results is obtained.

1. Introduction:

The optical-fiber-evanescent-wave absorption sensor is the most important, widely acclaimed and accepted sensor available today [1–7]. This is not only because of its electrical immunity, compatibility and very high sensitivity over the conventional sensors but also due to its wide spread industrial applications, remote and distributed sensing, on-line monitoring and wide range of applicability. Much research on evanescent field absorption sensors has concentrated on multi-mode plastic-clad-silica (PCS) fibers. Operation of these sensors is based on the modulation of the light intensity propagating in the fiber by the measurand. The advantage of intensity modulated sensors lies in their simplicity of construction and compatibility with multi-mode fiber technology. In evanescent wave absorption sensors, plastic cladding is replaced by an absorbing fluid so that the core can be exposed directly to the absorbing fluid. If light of wavelength close to the peak absorption wavelength of the absorbing fluid is launched into the fiber, loss of transmitted light power occurs due to absorption of the evanescent field penetrating into the absorbing medium. The loss in transmitted power increases with the increase of the concentration of the absorbing fluid. This modulated transmitted power is used to detect the concentration of the absorbing fluid. So far, the experimental results reported in the literature for various kinds of probe geometries [3–6] predicted a nonlinear dependence of evanescent absorbance on the fluid concentration and hence do not follow Beer's law of absorption, according to which the effective evanescent absorption coefficient is linearly proportional to the concentration of the fluid. A sensor with nonlinear response is not advantageous for application oriented purposes. This nonlinear dependence can be attributed to the activity of the silica-core towards the absorbing fluid [5,7]. Recently we have shown that nonlinearity occurs due to adsorption of solute molecules on the surface of the silica core and the whole phenomenon has been shown to be pH dependent [7]. In the case of positively charged solute molecules, such as methylene blue dye dissolved in the deionized water, nonlinearity increases with the increase of the pH of the solvent. Thus to obtain linear response, either the sensor should be operated at very low pH (or at very high pH range in the case of negatively charged solute molecules) or the silica surface reactivity should be prevented. The first case limits the sensor application and is not practicable. Safaai-Jazi and Peterson [5] in their study suggested a novel technique to prevent the reactivity of the silica surface. In their sensor the cladding was partially removed. The removal of part of the cladding resulted in a very weak evanescent tail interacting with the solution and hence poor sensitivity of the sensor was obtained. To increase the sensitivity, Safaai-Jazi and Peterson [5] used several fibers in the form of a bundle. In this paper we present a novel and much simpler technique for designing a fiber-optic evanescent wave absorption sensor with linear response and at the same time high sensitivity using a single fiber only. Recently, Gupta et al. [6] proposed a fiber optic evanescent field absorption sensor based on a U-shaped probe. The influence of the bending radius of the probe on the sensitivity of the sensor was studied experimentally. The sensitivity of the sensor was found to increase with the decrease of the bending radius of the probe. These results were shown to match qualitatively with the theoretical results obtained using a two-dimensional treatment and meridional ray analysis. For a fiber of 600 μm diameter and 0.213 cm bending radius of the probe, six fold increase in sensitivity over the straight probe was reported. Because of the high sensitivity, in the present paper, we have used a U-shaped probe. Since the U-shaped probe cannot be fabricated without removing the cladding, we first constructed the U-shaped probe and then a thin film of polymer was developed on the core of the U-shaped probe to prevent surface reactivity. The polymer film developed has refractive index less than that of the core and has negligible reactivity towards the solution. The experimental results obtained establish the linear response, increased sensitivity and good reproducibility.

2. Experimental

Fig. 1 illustrates the schematic diagram of the sensor system. A light source, sensing probe and detector constitute the main part of the sensor. To fabricate the sensing probe, a PCS (plastic-clad silica) fiber of 600 μm diameter and 0.17 numerical aperture (NA) with core refractive index of 1.457 was used. These values give 1.443 as the refractive index of the cladding and 82° as the critical angle of the fiber. The total length of the fiber used in the experiment was about 35 cm. About 5 cm length of cladding was removed from the central region of the fiber. After removing the cladding, the core was cleaned with acetone and first exposed to a flame at about 700°C. It was then slowly bent until it became U-shaped. The temperature of the flame was controlled by proper mixing of liquid petroleum gas and oxygen. The uniformities of the core diameter and the bending radius were checked using a travelling microscope. The experiments were performed only with those probes that were uniform in core diameter and the bend was close to U-shape. Before coating the probe, knowledge of the penetration depth of the evanescent field was required. For a liquid of refractive index n_2 surrounding the probe, the penetration depth is given by [8]

$$d_\mathrm{p} = \frac{\lambda}{2\pi n_1\left(\cos^2\theta_\mathrm{c} - \cos^2\theta\sin^2\theta_\phi\right)^{1/2}},$$

where λ is the wavelength of light launched into the fiber in free space, n_1 is the refractive index of the core, θ_c $(=\sin^{-1}(n_2/n_1))$ is the critical angle of the sensing region with respect to the normal on the core cladding interface, θ is the angle of the ray with the normal to the core-cladding interface and θ_ϕ is the skewness angle [8]. In the case of a meridional ray the skewness angle is equal to $\pi/2$. If all the bound rays are launched at the input end of the fiber then θ, for the fiber used in the present study, varies from 82° to 90°. When the ray enters the bent region its angle changes with respect to the normal to the interface [6]. At the outer surface the angle changes from

$$\phi_1 = \sin^{-1}\left[\left(\frac{R+h}{R+2\rho}\right)\frac{n_\mathrm{cl}}{n_1}\right]$$

to

$$\phi_2 = \sin^{-1}\left[\frac{R+h}{R+2\rho}\right],$$

where R is the bending radius of the probe, ρ is the radius

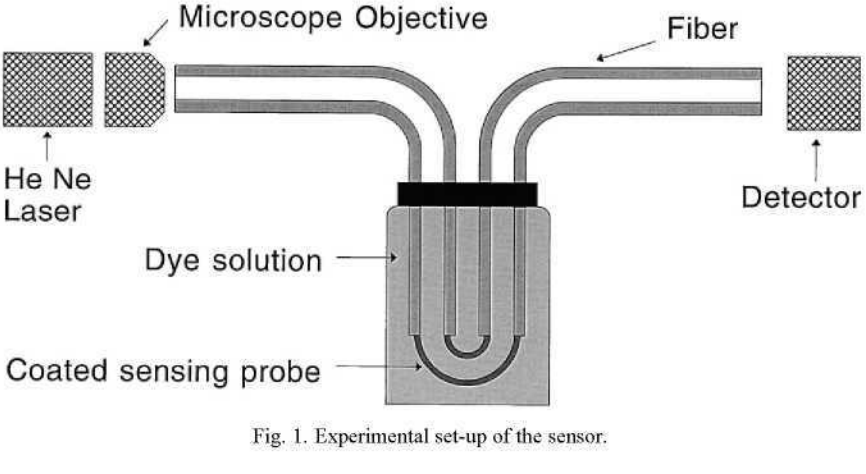

Fig. 1. Experimental set-up of the sensor.

of the fiber core and h is the distance of the ray at the entrance of the bent region from the inner core–cladding interface. At the inner surface, the angle changes from

$$\delta_1 = \sin^{-1}\left[\left(\frac{R+h}{R}\right)\frac{n_{\text{cl}}}{n_1}\right]$$

to $\delta_2 = 90°$. The calculated values of the penetration depth for the U-shaped probe of 0.5 cm bending radius and for different values of h and θ_ϕ are tabulated in Table 1. It may be noted that in the case of a straight fiber ($R = \infty$), d_p varies from 169 to 180 nm while in the case of a bent fiber with $R = 0.5$ cm, it varies from 169 nm to 612 nm. The increase in penetration depth increases the absorption of the evanescent field by the absorbing fluid which results in increase of the sensitivity of the sensor. Thus decrease of the bending radius increases the penetration depth and hence the sensitivity. This has also been shown both theoretically and experimentally by Gupta et al. [6].

To coat the U-shaped probe, it was washed with soap solution and then treated with 30% HNO_3 for about 10 min. After this, it was washed with de-ionized water (pH < 7) and then cleaned with acetone. Polyvinylidene fluoride (PVDF), a polymer, was used to coat a thin film over the U-shaped probe. PVDF is available in powder form and is soluble in dimethylformamide at approximately 100°C. Its melting point, water absorption and the refractive index are 210.2°, 0.04% and 1.42 respectively. To coat, PVDF with dimethylformamide was heated in the 100°–120°C range of temperature until a clear transparent solution of yellow color was obtained. Dip-coating method was used to develop the polymer film. To this end, the U-shaped probe was exposed to the polymer solution for about one hour and then the fiber was pulled at a constant speed of 10 cm/min. During the process, the temperature of the polymer solution was maintained at about 80°C. After removing from the polymer solution, thermal treatment was given to the probe for 3 hours keeping it in a furnace and maintaining its temperature at approximately 200°C. A very thin transparent film resulted over the bare U-shaped fiber probe. The film thickness and its refractive index were measured using the Abeles method [9]. The refractive index was found to be 1.42 and the thickness was calculated to be 130 nm. The film thickness is much less than the range of penetration depths of various guided rays of the U-shaped probe of 0.5 cm bending radius. In the present sensor the bending radius of the probe fabricated was 0.13 cm. For such a probe the penetration depth will further increase. The coated U-shaped probe was fixed in the cover of a glass cell of 20 ml capacity using an adhesive paste. Light from a He-Ne laser, operating at 632.8 nm was focused using a microscope objective (NA = 0.4, 20 ×) on the input face of the fiber. The other end of the fiber was connected to a power-meter. For the experiment, methylene blue dye dissolved in deionized water was used as the fluid because its peak absorption is close to the wavelength of the He-Ne laser.

Table 1
Penetration depths for the bending radius, $R = 0.5$ cm in the sensing region

S. No.	θ_ϕ	h	d_p (nm) ($82° < \theta < 90°$)	
			Outer surface	Inner surface
1	0	0	169.24	169.24
		2ρ	169.24	169.24
2	$\pi/4$	0	287.23–270.03	174.30–169.24
		$\rho/2$	241.83–230.69	169.24
		ρ	212.12–204.06	169.24
		$3\rho/2$	190.70–184.46	169.24
		2ρ	174.30–169.24	169.24
3	$\pi/2$	0	unguided	179.85–169.24
		$\rho/2$	unguided–612.65	169.24
		ρ	323.88–276.13	169.24
		$3\rho/2$	223.17–204.70	169.24
		2ρ	179.85–169.24	169.24

3. Results and discussion

To study the response characteristics of the sensor, measurements were carried out with methylene blue dye solution of different concentrations. The transmitted powers through the fiber were measured separately for the dye solution (P) and the de-ionized water (P_0) in the glass cell. These values along with the length of the unclad portion of the fiber were used to calculate the evanescent absorption coefficient from the following relation:

$$\gamma = \frac{2.303}{L}\log_{10}\left(\frac{P_0}{P}\right),$$

where L is the length of the U-shaped sensing region. After each measurement with dye, the cell and the fiber probe were cleaned with de-ionized water. The sensor response, illustrating the dependence of the evanescent absorption coefficient on the concentration level of the dye over a range of 1.5 μM to 25 μM is shown in Fig. 2 for the bending radius of the probe equal to 0.13 cm. It may be noted that the response of the sensor is linear indicating the absence of charge accumulation and surface loading over the sensing probe and hence surface reactivity. Gupta and Khijwania [7] obtained 0.0024 cm^{-1} as the evanescent absorption coefficient of the methylene blue dye of 10 μM concentration and pH close to 2 in the case of an uncoated straight core ($R = \infty$) sensing probe. At low pH the response of the sensor was linear. If we compare this value of γ with the one obtained in the present study for coated U-shaped probe ($\gamma = 0.17\ \text{cm}^{-1}$) we find that for the same

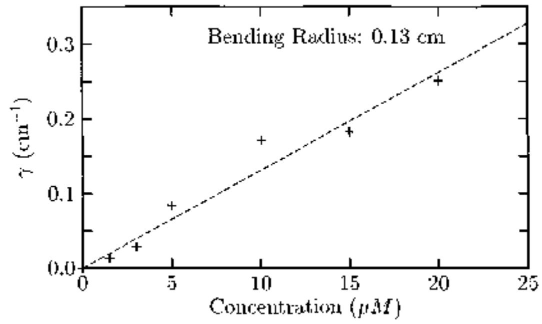

Fig. 2. Variation of the evanescent absorption coefficient (γ) with the dye concentration for the polymer coated U-shaped sensing probe.

sensing length, the present sensor is more sensitive than the straight probe. To achieve the same sensitivity one will have to use about 70 straight fibers. The effect of coating can be noticed if we compare the response of the present sensor with the response of an uncoated U-shaped sensor of larger bending radius at low concentration (less than 12 μM, up to which the response of the uncoated probe sensor is approximately linear) [6]. The coating has decreased the value of the evanescent absorption coefficient for a given concentration. Although the uncoated U-shaped probe is more sensitive with respect to the proposed sensor, it has a very low linear concentration range. The present sensor has large dynamic range. These experiments were repeated with identical probes and a good degree of reproducibility in the results was noticed. The sensitivity of the sensor can be further increased if the bending radius is reduced. However it does not influence the linearity of the response curve.

In summary, we have proposed a novel technique and the design of a fiber optic evanescent field absorption sensor to obtain linear response together with high sensitivity. The silica surface reactivity with the fluid, which is the main reason of nonlinear response, has been prevented by coating a polymer film over the bare core of an highly sensitive U-shaped probe.

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