Design and Fabrication of Evanescent Wave Fiber Optic Sensor

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ABSTRACT
Optical fibers have been widely used in the field of sensors. In this paper single mode fiber optic sensor is designed and constructed for detecting the concentration of solutions based on the excitation of the evanescent wave at the cladding/core interface. Two wavelengths of 650nm and 850nm have been used. 3 cm of cladding has been removed in the middle of 1 m SMF-28 by using Hydrofluoric acid (HF). The sensing region is immersed in various concentrations of Sodium Chloride (NaCl) and Sucrose solutions. Light Emitting Diode (LED) is connected to one end of the fiber and the other end to Optical Spectrum Analyzer and/or power meter. As the concentration of solution increases the intensity decreases, the output power decreases, and the absorption of evanescent wave increases. The sensitivities of this sensor for sucrose solutions at 850 nm and 650 nm are 0.18 nW/(%w/v) and 0.1637 nW/(%w/v), respectively and for NaCl solutions at 850 nm and 650 are 0.437 nW/(%w/v) and 0.337 nW/(%w/v), respectively.

KEYWORDS: Concentration, Single Mode Fiber, Evanescent Wave, Intensity Modulated Fiber Optic Sensor.

INTRODUCTION
In recent years optical fiber has been used in sensing application such as temperature, vibration, strain and acoustics [1]. Optical fiber sensor has been improved to measure another various physical properties, like light intensity, liquid level, radiation, chemical changes, and refractive index [2]. It is designed to collect data by an optical fiber; the measurand alters a specific physical property and causes a change in the characteristics of transmitted light along the optical fiber [3].

In the past various refractive index sensors have been demonstrated for different applications but they have disadvantage of weight and big size [4]. Nowadays fiber optic refractive index sensors are widely used in various fields such as chemical, biochemical, and in an industry field. They have several advantages such as small size, ultra fast response, corrosion resistance, remote sensing, high sensitivity, immunity to electromagnetic interference [5].

Fiber optic sensor can be classified according to the operating principle into phase, polarization, intensity, and frequency sensor [6]. Among all of these sensors the Intensity modulated fiber optic sensor combine the simplest structure and the lowest cost [7]. In intensity modulation the transmitted light intensity is modulated by the measurand [8].
Theory:
1. Evanescent Field:
   The light propagates through an optical fiber by total internal reflection [9]. An evanescent wave occurs when the light is not completely confined to the core but distributes into the cladding region. The portion of light in the cladding called an evanescent wave as shown in Figure (1) [10].

![Figure 1: Schematic diagram of the evanescent wave distribution in the sensing fiber [9].](image1)

The electric field decays exponentially at the core/cladding interface as follows [9]:

$$E = E_0 e^{-\frac{Z}{d_p}}$$

(1)

Where $d_p$ is the penetration depth, $z$ is the distance from the core/cladding interface, $E_0$ is the electric field at the interface [9].

The intensity of evanescent wave also decays exponentially at core/cladding interface as follows [11]:

$$I = I_0 e^{-\frac{Z}{d_p}}$$

(2)

The penetration depth is given by [8]:

$$d_p = \frac{\lambda_0}{2\pi\sqrt{n_1^2 \sin^2 \theta - n_2^2}}$$

(3)

Where $n_1$ is the refractive index of core, $n_2$ is the refractive index of cladding, $\lambda_0$ is the wavelength of light in the vacuum, $\theta$ is the angle of incidence, because there is no absorption in the cladding, no power loss is measured along the fiber. When the cladding is replaced by an absorbing media, the transmitted power is reduced and the intensity of evanescent wave is decreased. The losses are resulted from the interaction between solution and the evanescent wave. A bigger value of $d_p$ indicates a bigger loss of the power and higher sensitivity of the sensor [9].

2. Evanescent Field Concentration Sensor:
   To enable the interaction between the evanescent wave and the solution, the fiber structure must be modified by chemical etching or polishing of the cladding layer [12]. As a portion of cladding is removed, the evanescent wave can interact with solution as shown in Figure (2), and the concentration can be detected by measuring the losses in the output power [9].

![Figure 2: Schematic diagram of the solution that surrounds the core of the optical fiber sensor [9].](image2)

The transmitted power in the cladding which is replaced by solution is given by [13]:

$$P = P(0)\exp(-\gamma CL)$$

(4)
$P(0)$ and $P$ are respectively, the transmitted power through the fiber without and with an analyte over the removed portion of length $L$. $C$ is the concentration of solution and $\gamma$ is the evanescent field absorption coefficient is defined as [13]:

$$\gamma = r_f \alpha_m$$

(5)

Where $\alpha_m$ is the bulk absorption coefficient of solutions, $r_f$ is the effective fraction of the total transmitted power in the sensing region [13].

The absorbance of evanescent wave is given by:

$$A = \ln[P(0)/P]$$

(6)

Equation (7) is obtained by substituting (4) and (5) into (6)

$$A = r_f \alpha_m CL$$

(7)

The absorbance Equation is directly proportional to the length of sensing region, effective fraction of the transmitted power in the uncladded region, concentration of solution [13].

Experimental Method:

Nacl and Sucrose have been used as guiding liquids with various concentrations. The concentrations of Nacl solutions range from 5% to 25% and for Sucrose solutions range from 10% to 50%. The refractive index for Nacl and Sucrose solutions at each concentration is measured by using Abbe refractometer.

3 cm of outer plastic jacket in the middle of 1 m of SMF-28 has been removed by immersing the fiber in acetone; the buffer is also removed by acetone. The cladding is partially etched by using hydrofluoric acid (HF) with 40% concentration for 35 minutes to obtain high sensitive region to the surrounding concentrations. Figure (3) shows the experimental setup schematic diagram of evanescent wave fiber optic sensor.

![Fig. 3](image-url)

The experimental setup schematic diagram of evanescent wave fiber optic sensor.

The system consists of Light from light emitting diode LED (Fiber Optic Communications Training System EF-970/T promax) with an operating wavelength 650nm is launched into one end of SMF-28, single mode fiber is settled in small container with (5cm length and 2cm height) so as prevent the movement of fiber during the work, the sensing length (etched section) of the fiber is immersed in distilled water and different concentrations of Sodium chloride and Sucrose solutions. The process is repeated at an operating wavelength 850nm (Fiber Optic Communications Training System EF-970/T promax). The output is taken for the two wavelengths on power meter (Fiber Optic Communications Training System EF-970/R promax) and optical spectrum analyzer (HR 2000). The experimental setup arrangement of evanescent wave fiber optic sensor is shown in Figure (4).
Fig. 4: The experimental setup arrangement of evanescent wave fiber optic sensor.

RESULTS AND DISCUSSION

Figures (5) and (6) show the relationship between refractive index and concentration of Nacl and Sucrose solutions, respectively.

Fig. 5: The relationship between concentration and refractive index of Nacl solutions.
From the figures the refractive index is directly proportional to the concentration, as concentration of guiding liquid increases refractive index increases.

The sensing region is immersed in various concentrations of NaCl solutions range from 5% to 25% and Sucrose solutions range from 10% to 50%. The sensitivities of this sensor for sucrose solutions at 850 nm and 650 nm are 0.18 nW/(%w/v) and 0.1637 nW/(%w/v) respectively, and for NaCl solutions at 850 nm and 650 nm are 0.437 nW/(%w/v) and 0.337 nW/(%w/v), respectively, as shown in Figures (7) and (8). According to Equation (4) as the concentration of solution increases the output power decreases at both wavelengths 650 nm and 850 nm.

**Fig. 6:** The relationship between concentration and refractive index of Sucrose solution

**Fig. 7:** The relationship between output power and concentrations of sucrose solutions.
Fig. 8: The relationship between output power and concentrations of NaCl solutions.

The obtained results from the optical spectrum analyzer at wavelengths of 650 nm and 850 nm show that as the concentration of Sucrose solution increases, the intensity decreases at both wavelengths, in addition it shows that the wavelength is slightly shifted toward a blue region with increasing the concentration of sucrose solution at both wavelengths of 850 nm and 650 nm as shown in Figures (9) and (10), respectively.

Fig. 9: Intensity spectra of sucrose solutions at an operating wavelength 850 nm.
Fig. 10: Intensity spectra of sucrose solutions at an operating wavelength 650 nm.

The same behavior is obtained for Nacl solution which shows that the wavelength is slightly shifted toward a blue region with increasing the concentration of Nacl solution at both wavelengths of 650nm and 850nm as shown in Figures (11) and (12), respectively.

Fig. 11: Intensity spectra of Nacl solutions at an operating wavelength 850 nm.
By implementing Equation (6) the results show that as the concentration of solution increases the absorbance of evanescent wave increases at both wavelengths 650nm and 850 nm, the change in the absorbance will lead to intensity modulation. The relationship between concentrations of NaCl and Sucrose solutions and absorbance are shown in Figures (13) and (14), respectively.

**Fig. 12:** Intensity spectra of NaCl solutions at an operating wavelength 650 nm.

**Fig. 13:** The relationship between evanescent wave absorbance and concentrations of Sucrose solutions at an operating wavelengths 850 nm and 650 nm.
Fig. 14: The relationship between evanescent wave absorbance and concentrations of Nacl solutions at an operating wavelengths 850 nm and 650 nm.

Conclusion:
A fiber optic sensor based on the excitation of evanescent wave at the interface between core and cladding has been designed and fabricated for high sensitive measurement of various concentrations of Nacl range from 5% to 25% and sucrose range from 10% to 50%. The sensitivity of sensor for concentrations of sucrose solutions is 0.18 nW/ (%w/v) at an operating wavelength of 850 nm, and 0.1637 nW/ (%w/v) at an operating wavelength of 650 nm, and the sensitivity of sensor for concentrations of Nacl solutions is 0.437 nW/ (% w/v) at an operating wavelength of 850 and 0.337 nW / (% w/v) at an operating wavelength of 650 nm. This system can be used for measuring the concentration of Nacl and Sucrose in various applications such as industry, medical, environment controlling systems, and monitoring the quality of drinking water.

REFERENCES