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Intrinsic Intensity Modulated Tapered Glass Multimode Fiber Optic Temperature Sensor

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Abstract: Optical fiber sensors playing a dominant role over the conventional sensors in the sensing of innumerable environmental parameters during last few decades due to their tremendous advantages in various aspects. In this paper an experimental study has been made of the variation of the power output using plastic (PCS) fibers with a tapered glass rod as sensing probe at the sensing zone of the sensor design. This tapered glass rod is passed through metallic encapsulation containing the liquid and the temperature of the liquid is varied gradually. Power launched from the source operating at the wavelength of 633 nm transmits through the input fiber via the tapered glass rod and couples into the output fiber and emerges at the output end and can be recorded from the power meter. A correlation is formed between the power output, with the rise in the temperature of the liquid. Theoretical explanation for the variation of power with temperature offered on the basis of intensity modulation by evanescent wave absorption of the light wave in the liquid cladding. The possibility of a simple, cost effective and reliable design for the sensing of temperatures of various liquids is discussed. By varying geometrical parameters of the tapered glass rod, the flexibility of shifting the dynamic range of the sensor from one operating range to the other also been interpreted.

Keywords: Tapered glass rod, PCS fibers, intensity modulation, evanescent wave absorption, sensing of temperature, geometrical parameters.

I. INTRODUCTION

The optical fiber sensor systems are indispensable in almost all walks of life starting from consumer, defense, oil industry, biochemical, medical, food processing, chemical, beverages, under sea, as well as space applications. The optical fiber sensors are used to provide online measurement of various environmental parameters like temperature, vibration, pressure, strain, liquid level, fluid flow, rotation, acceleration, displacement, toxic gas, pH, humidity, magnetic field, electric field and many more. Since its first inception, over the past 45 years, the developments in fiber optic sensor technology are phenomenal [1 – 4]. The process of fiber optic sensing is a multidisciplinary as it bases on various physical and chemical phenomena. The essential operation of a sensor is to cause a change from one form of input energy associated with the measurand to a single valued change in output optical energy for the detection and measurement. The input signal and its energy for various measurands may be in different forms.

(a) Thermal – temperature, temperature difference, heat flow etc.
(b) Mechanical – force, strain, pressure, stress, mass, flow, etc.
(c) Electrical – current, resistance, voltage, capacitance, etc.
(d) Magnetic – magnetic field, permeability, flux density, etc.
(e) Chemical – pH, chemical composition, oxidation reduction potential, etc.
And so forth.

The optical fibers with versatile advantages like light in weight, small and compact in size, low power consumption, non electromagnetic interference, high sensitivity and longevity, fast response time, working in rugged environment, easy multiplexing, remote sensing are rapidly replacing the traditional sensors in almost all fields of applications. Many kinds of optical fiber based sensor systems like acoustic sensor for undersea uses, rotation sensor for aircraft or missile systems, current sensor for electrical power establishment, gas and biosensor for oil field and biomedicine and instrumentation systems, etc. are reported by many researchers.

The schematic presentation of the general configuration of the optical fiber sensing system in block diagram is shown below (figure 1).

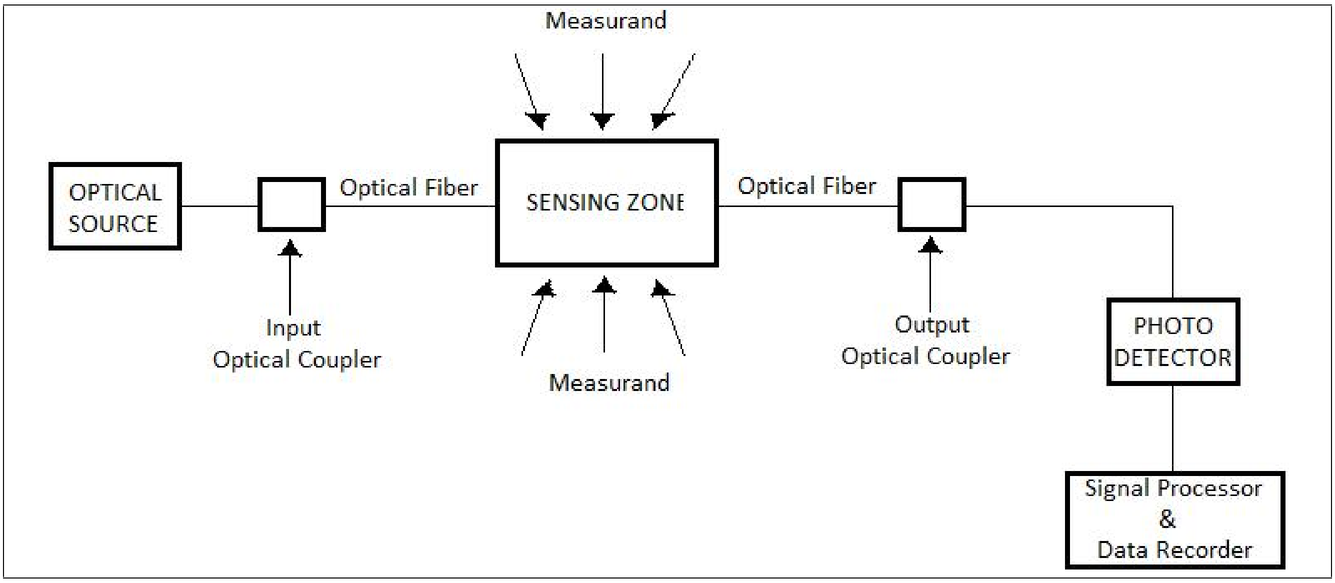


Fig. 1: Schematic block diagram of optical fiber sensor system.

Light from optical source (laser or LED) is launched into the input optical fiber, guided through measurand region and finally collected by the photo-detector. At the region of sensing, the light gets modulated by the measurand in terms of its amplitude, phase, wavelength or polarization by the chemical, physical or biological phenomena. The intensity of the modulated light of the fiber sensor depends on several discrete parameters given by

$$\textit{The feature of the output signal} = PS \times EC \times TE \times MF \times RD$$

Where,

PS ———> Power of light source
EC———> Efficiency of input and output couplers for coupling the signal into the fiber
TE———> Transmission efficiency of the optical fiber
MF———> Modulation Functional response of light during passage of signal through measurand
RD———> Responsivity of Photo-detector

The optical fiber sensors generally grouped into two basic classes, namely – active or intrinsic and passive or extrinsic. In case of first category of sensors, the quantity to be measured acts directly on the fiber itself to modify the light quality during its passage through it, on the other hand in the case of extrinsic sensor, the fiber merely acts as conduit to transmit the light to and from the sensor head.

Many methods have been developed for the measurement of temperature using liquid crystals, phosphor or optical fiber itself as a sensing material have been reported in the literature [5 – 6]. A fiber optic temperature sensor responding to the optical absorption of a semiconductor has also been reported [7]. Using optical fibers, a variety of methods have been employed as means of measuring temperature involving the effects of intensity modulation [8]. The advantage of intensity modulated sensors lies in their simplicity of construction and their being compatible to the multimode fiber technology. The phase modulated fiber optic sensors theoretically offer higher sensitivity as compared to intensity modulated sensors but they necessary require interferometric set-up with associated complexity in construction. However, when high degree of accuracy is needed, it is desirable to go in for interferometric methods. For remote and distributed sensing applications, evanescent field absorption fiber optic sensors have become popular during the last few years [9 – 11]. These sensors functions based on the attenuated total refractance (ATR) spectroscopy mechanism. When light travels from a medium of high index of refraction (core) to a medium of less index of refraction (cladding), an evanescent wave propagates into the rarer medium, and the amplitude of the wave decreases exponentially in the rarer medium with a characteristic penetration depth in the cladding medium [12]. The evanescent wave intensity decreases in the rarer medium if the medium is of absorbing nature, results a remarkable reduction in the power transmitting in the denser medium. The attenuation further increases if the number of reflections at the interface increases. Thus an unclad optical fiber (Tapered glass rod in the present case) can be employed as an ATR sensing probe. Further in the tapered region, most of the axial rays will be converted into evanescent waves, due to the magnitude of the gradient of the thickness of the taper from thick end to the reduced end and also of tapered angle. Lesser the gradient of the taper and hence the taper angle in the sensing zone, smaller the power loss into the cladding. In addition to this a fraction of axial power also enters into the cladding (liquid cladding that surrounds the glass taper in the present case) due its absorptive nature. Once the geometrical parameters of the taper are fixed, then the total absorption simply depends on the absorptive nature of the liquid that surrounds the tapered zone.

II. EXPERIMENTAL DETAILS

Among different fiber optic temperature sensors, the non interferometric, non luminescent temperature sensor is the simplest in design, as it requires only light guiding low cost multimode optical fibers and a temperature sensitive material. The sensing materials like GaAs, CdTe, Si, etc. exhibit prominent changes of their optical absorption, transmission and reflection qualities with the variation of temperature. A borosilicate glass is tapered so as to maintain an end ratio of 0.5 between the two ends of the tapered portion of the glass rod, by using heat treatment techniques, is used in this experiment as a sensing element. Two plastic optical (PCS) fibers of 200/ 230 µm diameters having 0.5m length each in which one is used as input fiber and the other as output fiber are employed in the present experiment. A light source operating at the wavelength of 633 nm was used as input light. The schematic of experimental arrangement is shown in figure 2.

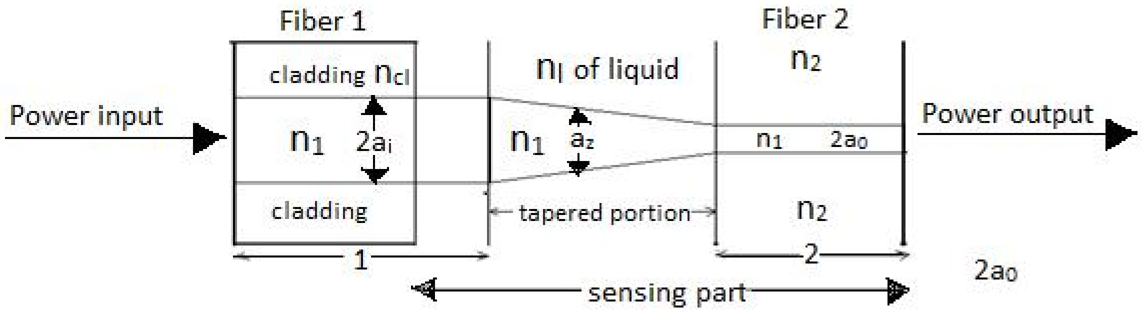


Fig. 2: Experimental arrangement of tapered fiber optic sensor

The thick end of the taper is connected to the input fiber (fiber 1) by using a suitable connector and the reduced end of the taper is connected to the output fiber (fiber 2). The input and the output fibers are connected to the light source operating at the wavelength of 633 nm and the benchmark power meter respectively. The tapered portion can be thought of as interconnection between two fibers: one of core diameter $2a_i$, and the other of core diameter $2a_0$ $(a_0 < a_i)$. Fibers 1, 2 and tapered interconnecting zone all having the same core and cladding refractive indices n_1 and n_2, respectively except for the initial section of fiber 1 in which the cladding index is n_{cl}. If P_0 represents the total power injected into the guided modes of fiber 1, then the power output in fiber 2 is given by [13]

$$P_b = P_0 \frac{n_1^2 - n_l^2}{R^2(n_1^2 - n_{cl}^2)} \tag{1}$$

Where,

$R = a_i / a_0$ Represents the taper ratio

n_1 = Refractive index of the core

n_{cl} (or n_2) = Refractive index of the cladding

n_l = Refractive index of the liquid

It is evident from this equation that power coupled to fiber 2 through taper increases linearly with proportional decrease in n_l^2.

Theory: Relating the output power as a function of refractive index of the liquid surrounding the taper region in a tapered multimode optical fiber:

Consider the figure 3 bellow.

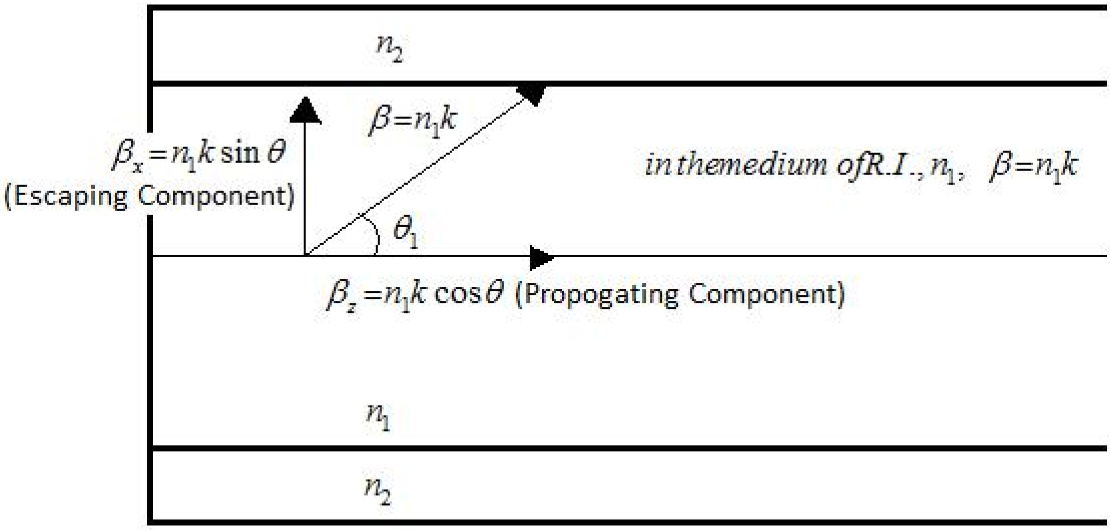


Fig. 3: Mode propagation in fiber 1 in terms of its propagation constant

The z- component of a mode propagating in fiber 1 with effective index n_1 can be written as

$${}_1 = n_1 \cos \overline{}_1 \tag{2}$$

This mode gets transformed into an escaping component (or mode) in the taper as

$${}_{z,taper} = a(z)\sin \overline{}(z) = a_i \sin \overline{}_1 \tag{3}$$

Where,

$a_i \sin \overline{}_1$ - The escaping component in fiber 1

$\overline{}(z)$ - The corresponding propagation angle in the taper region.

$a(z)$ - Represents the radius of the taper at a distance Z from its thick end.

Thus the mode of ${}_1$ will get transformed through the taper as ${}_{z,taper} = a(z)\sin\bar{\ }(z)$ to a mode of ${}_2$ in fiber 2, given by

$${}_2 = n_1 \cos\bar{\ }_2 \qquad \text{(as in equation (1))} \tag{4}$$

But the escaping (or transverse) mode in fiber 2, as in equation (3), can be written as

$${}_x = a_0 \sin\bar{\ }_2 \tag{5}$$

The escaping components in fiber 1 and 2 are equal. Therefore

$$a_i \sin\bar{\ }_1 = a_0 \sin\bar{\ }_2$$

Or

$$\sin\bar{\ }_2 = \frac{a_i}{a_0}\sin\bar{\ }_1 \tag{6}$$

$$\cos\bar{\ }_2 = \left[1-\sin^{2}\bar{\ }_2\right]^{1/2} = \left[1-\left(\frac{a_i}{a_0}\right)\sin^{2}\bar{\ }_1\right]^{1/2} \tag{7}$$

But from equation (1), $\cos^{2}\bar{\ }_1 = \frac{{}_1^{2}}{n_1^{2}}$

Therefore, $\sin^{2}\bar{\ }_1 = 1-\frac{{}_1^{2}}{n_1^{2}}$ (8)

Substituting equation (8) in (7),

$$\cos\bar{\ }_2 = \left[1-\left(\frac{a_i}{a_0}\right)^{2}\left(1-\frac{{}_1^{2}}{n_1^{2}}\right)\right]^{1/2} \tag{9}$$

Now substituting equation (9) in (4)

$${}_2 = n_1\left[1-R^{2}\left(\frac{n_1^{2}-{}_1^{2}}{n_1^{2}}\right)\right]^{1/2}$$

$${}_2 = \left[n_1^{2}-R^{2}(n_1^{2}-{}_1^{2})\right]^{1/2} \tag{10}$$

Now for a mode to be guided fiber 2, one must have

$$ {}_{1} \geq \left[n_1^2 - \frac{n_1^2 - n_l^2}{R^2} \right]^{1/2} = {}_{\min} \qquad (11)$$

Modes with ${}_1 < {}_{\min}$ will enter into the liquid and can't enter into fiber 2

If ${}_1 = \left[n_1^2 - \frac{n_1^2 - n_l^2}{R^2} \right]^{1/2}$ so that ${}_2^2 = n_l^2$ from equation (10) otherwise ${}_2$ becomes zero or negative.

If P_0 represents the total power injected into the guided modes of fiber 1, then the power in the modes with ${}_1 > {}_{\min}$ will be

$$P_b = P_0 \left[\frac{n_1^2 - {}_{\min}^2}{n_1^2 - n_{cl}^2} \right] \qquad (12)$$

Which on substitution of ${}_{\min}$ from equation (11), becomes

$$P_b = P_0 \frac{n_1^2 - n_l^2}{R^2 (n_1^2 - n_{cl}^2)} \qquad (13)$$

From this equation the power coupled to fiber 2 through the taper decreases with proportional increase in n_l^2.

Immersing the taper zone in a liquid of refractive index $n_l < n_1$, the power reaching the output end can be recorded from the power meter. Immersing the taper subsequently in a number of other liquids and monitoring the corresponding power reaching the fiber 2, one can generate a calibrated curve for a given fiber taper. Thus by measuring the power exiting from fiber 2 when the taper is immersed in a liquid of unknown refractive index, one can use this calibration curve to determine the refractive index of the unknown liquid.

The same technique can be used to construct a temperature sensor by encapsulating the taper with a metallic or glass encapsulation filled with a liquid whose refractive index is temperature sensitive.

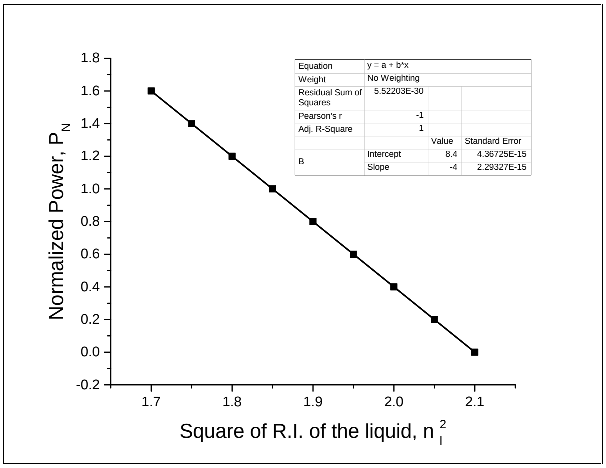
In the present experiment, the tapered sensing arrangement is dipped in Glycerin (R. I. is 1.483) in an encapsulation container. The liquid with taper dipping in it is then heated and the variation in the output power is noted at different temperatures. Simultaneously, the refractive index of the liquid is also noted using Abbe's refractometer.

III RESULTS AND DISCUSSION

The light launched into the fiber 1 when sensor dipped into the Glycerin, propagates through the taper and enters into fiber 2 and emerges as output power in the detector. The output power is a function of concentration of the liquid that surrounds the taper. The output power concentration of the liquid cladding and hence the refractive index of the liquid is increases, the power output decreases and vice versa. During the course of interaction of light with the liquid column, the guided light penetrates into the liquid cladding through a distance of approximately a few wavelengths as an evanescent wave of waveguide mode [14]. The absorption of light into the liquid cladding depends on following parameters.

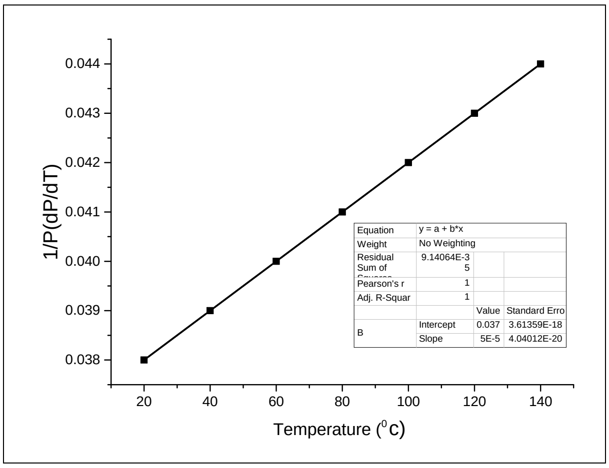
- The length of the taper region
- Angle of the taper
- Absorptive coefficient of the liquid cladding
- Temperature of the liquid
- Refractive indices of core, cladding, and of the liquid
- Taper ratio

It is well known that the refractive index is inversely proportional to the temperature of the liquid cladding. That is by varying the temperature, the refractive index varies and power reaching the output also varies accordingly. When the temperature of the liquid column is increased, the refractive index of the liquid decreases and hence the power reaching the detector increases. The linear increase in power collected P_N (normalized power) at the output fiber with proportional decrease in n_l^2 is plotted in fig. 4, and the dependence of sensitivity of the tapered fiber optic temperature sensor on the temperature of the liquid is presented in figure 5.



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	5.52203E-30		
Pearson's r	-1		
Adj. R-Square	1		
		Value	Standard Error
B	Intercept	8.4	4.36725E-15
	Slope	-4	2.29327E-15

Fig. 4: Variation of normalized power with square of the refractive index of the liquid cladding



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	9.14064E-35		
Pearson's r	1		
Adj. R-Squar	1		
		Value	Standard Erro
B	Intercept	0.037	3.61359E-18
	Slope	5E-5	4.04012E-20

Fig. 5: Variation of sensitivity with temperature of the liquid cladding

The results from figures 4 & 5 clearly demonstrate the application of optical fiber tapered temperature sensors to measure the temperatures of liquids in the case where the liquids are otherwise inaccessible, hazardous or dangerous, inflammable or when the electromagnetic interference is likely to distort the measurement [15].

IV CONCLUSIONS

A tapered glass rod fiber optic temperature sensor has been demonstrated which can be used for measurement of temperatures of the liquids in situation where the liquids are otherwise inaccessible to the conventional sensors, or where the liquids are dangerous that their temperatures cannot be detected with ease, or the liquids are inflammable, or when the electromagnetic interference is likely to distort the measurement of the temperature. A theoretical study of the evanescent wave absorption phenomena with respect to the refractive index (concentration) of the liquid cladding around the tapered sensing probe has been undertaken. It is expected that by proper selection of the liquid in the encapsulation, based on the boiling and melting points, the dynamic range of the sensor can be shifted from operating at one range to the other range. The sensitivities of the tapered temperature fiber optic sensor is greater than most of the temperature sensors that can be designed by using optical fibers.

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