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Fiber Optic Displacement and Liquid Refractive Index Sensors with Two Asymmetrical Inclined Fibers

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Abstract: Fiber optic displacement sensor (FODS) with two asymmetrical inclined fibers is studied theoretically and experimentally. A liquid refractive index sensor (LRIS) is then demonstrated using the similar sensor set-up. The theoretical result of the FODS is in good agreement with the experimental result, verifying the feasibility of our theoretical model. The performance of FODS is strongly depended on core radius and diameter of fibers used as well as inclination angle of two asymmetrical fiber core. The maximum sensitivities of 0.2752, 0.3759 and 0.7286 mV/ μm are obtained at inclination angles of 10°, 20° and 30°, respectively. Meanwhile, the maximum linear ranges of 10.4 mm, 7 mm and 3 mm are obtained at inclination angles of 10°, 20° and 30°, respectively. The proposed LRIS produces the highest output different for increase in refractive index at displacement of 3.3 mm. At this distance, the output intensity increases almost linearly as a function of refractive index of the medium. *Copyright © 2009 IFSA.*

Keywords: Fiber-optic displacement sensor, Liquid refractive index sensor, Fiber-optic sensor

1. Introduction

Intensity modulation is one of the important methods that is normally used for displacement measurement in conjunction with multimode fiber. The fiber optic displacement sensor (FODS) has inherited many advantages such as virtues of simplicity, reliability and low cost [1]. To date, many works have been reported on the intensity modulation based FODS [2-5], which the probe consists of a pair of fibers used for transmitting and receiving the light. For instance, Buchade, et. al. [4] presented a FODS using two fibers inclined with a same angular angle and reported the sensitivity was enhanced compared with the conventional sensor with parallel bundled fibers. It also reported that the

performances of the FODS with two fibers are depended mainly on four parameters: the offset, the lateral separation and the angle between the transmitting and receiving fiber tips, and the angle of the reflector [6]. However, there is still a lack of research work on the FODSs with different geometry of the receiving fiber.

Another important fiber optic sensor is a liquid refractive index sensor (LRIS), which is vital to design of optical instruments and is also a great value in chemical applications. The knowledge of refractive index of a substance is useful in indentifying and determining the concentration of organic substances. The refractive index of liquid samples can be measured in many ways such as implementation of total internal reflection and prism coupling techniques [7-9]. For instance, Nath, et al [9] proposed a liquid refractive sensor based on the frustrated total internal reflection effect caused by refractive index change of a medium surrounding one optical fiber tip.

In this paper, a mathematical model for the intensity modulation FODS with two asymmetrical and inclined fibers is developed. The developed model is used to simulate the response of the sensor with different inclined fiber angles. Experimental validation of simulated results on the inclined fiber sensor is also carried out in this study. In this work, a new LRIS is also proposed using the similar set-up to detect a refractive index of liquid media. The liquid of which the refractive index is measured is filled up in the gap between probe and reflector. Depending upon the refractive index of liquid, angle of emittance will change which will affect the received output power by receiving fiber.

2. Sensor Design and Theoretical Analysis

Fig. 1 shows the geometry of the inclined displacement sensor, which consists of a transmitting fiber, receiving fiber and a reflector. The sensor performance is studied at various core radiuses of transmitting and receiving fiber. Fig. 1(a) (Fig. 1(b)) shows the geometry of the sensor in case of the receiving core is bigger (smaller) than the transmitting core. Two asymmetrical transmitting and receiving fibers are mounted at an angle ' θ ' with reference to the normal to the reflector. This ensures the receiving fiber core to collect the maximum power from emitting light cone of the transmitting fiber. The shortest distances between the sensor probe tips and reflector are x_1 and x_2 for transmitting fiber and receiving fiber, respectively. The dash lines inside the receiving fiber represents the size of the transmitting fiber. The image of transmitting (receiving) fiber is formed at a further distance x_1 (x_2) opposite to the transmitting (receiving) fiber beyond the reflector. The image fiber is thus seen located at $2x_1$ or $2x_2$ from the original position of the probe. Effectively the reflected light appears to form a cone and reaches the receiving fiber, which is parallel aligned in the cone as shown in Fig. 1.

As shown in Fig. 1, the core radius of the transmitting and receiving fibers are denoted as r_1 and r_2 , respectively. Meanwhile, the diameters of transmitting fiber and receiving fiber are r_{d1} and r_{d2} , respectively. We assume that the ratio between the core radius of two fibers is k_1 , $k_1 = r_1/r_2$ and the ratio of fiber diameter of the two fibers is $k_2 = r_{d1}/r_{d2}$. From the geometry analysis of Fig. 1, the distance between the two sides of image of transmitting and receiving fibers is given by:

$$f = |r_{d1} \times \cos(2\theta) - 2x_1 \times \sin(\theta)| \quad (1)$$

Then, the distance between two fiber core, D is obtained as:

$$D = f + \frac{r_{d2} - r_{d1}}{2} = f + \frac{r_{d2}(1 - k_2)}{2} \quad (2)$$

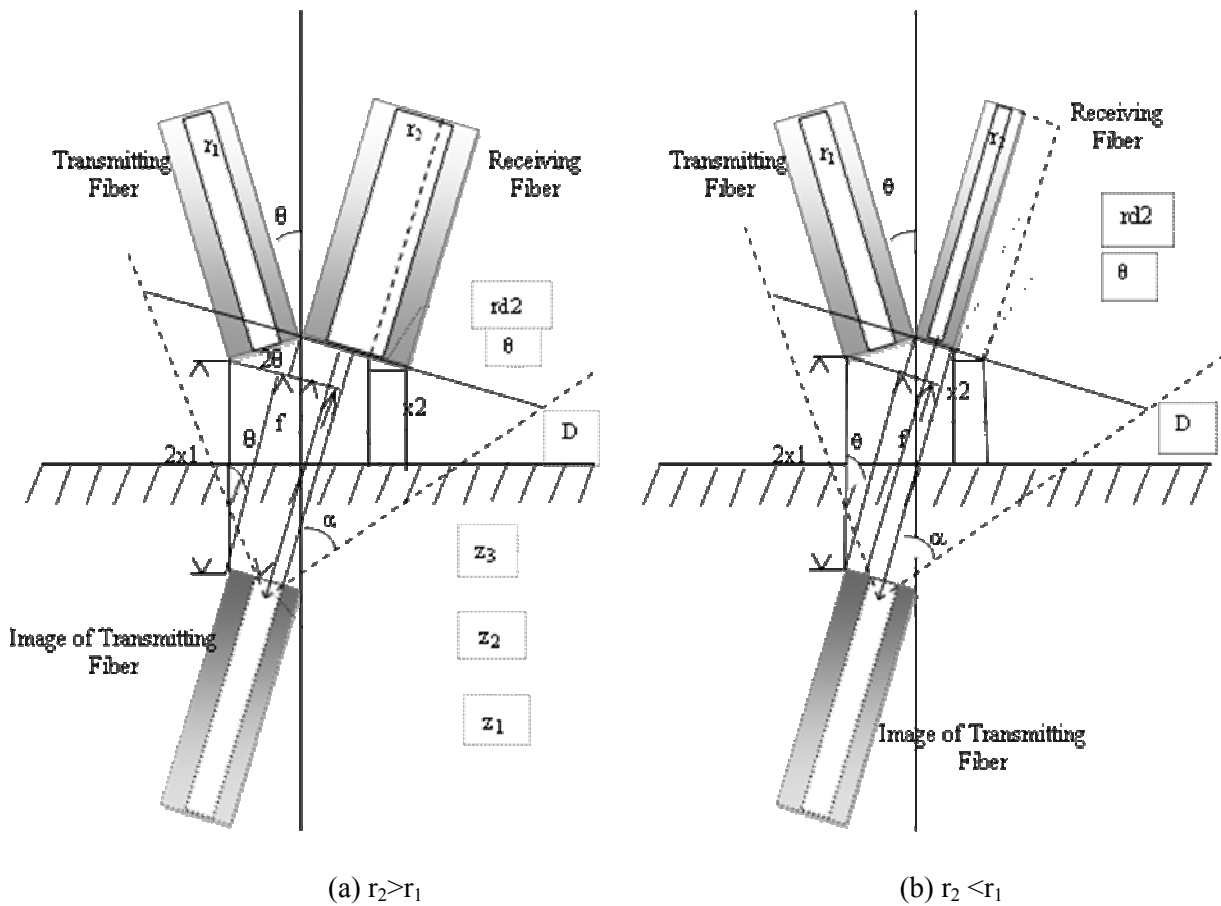


Fig. 1. The structure of sensor probes (a) $r_2 > r_1$; (b) $r_2 < r_1$.

The acceptance angle of transmitting fiber, α is given by $\alpha = \sin^{-1}\left(\frac{NA}{n}\right)$, where NA is a numerical aperture for the transmitting fiber. The distance between emitting points of transmitted light to the receiving flat core is denoted as z , which is given by:

$$z = z_1 + z_2 + z_3, \quad (3)$$

where $z_1 = r_1 \times \cot\alpha = k_1 r_2 \times \cot\alpha$, $z_2 = 2x_1 \times \cos(\theta)$ and $z_3 = r_{d1} \times \sin(2\theta) = k_2 r_{d2} \times \sin(2\theta)$ as illustrated in Fig. 1.

To analyze the power collected by the receiving fiber, we simply analysis the light inside the fiber by using a Gaussian beam approach. The irradiance of emitted light is obeying an exponential law according to

$$I(r, z) = \frac{2P_E}{\pi\omega^2(z)} \exp\left(-\frac{2r^2}{\omega^2(z)}\right), \quad (4)$$

where P_E is the emitted power from the light source, r is the radial coordinate and z is the longitudinal coordinate calculated by equation (3). $\omega(z)$ is the beam radius which is also a function of z ,

$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$. The waist radius ω_0 and Rayleigh range z_R are the important parameters in the

Gaussian Beam function. The optical power received by the receiving fiber can be evaluated by integrating the irradiance, I over the surface area of the receiving fiber end, S_{r_2}

$$P(r, z) = \int_{S_{r_2}} I(r, z) dS_{r_2} \quad (5)$$

To simulate conveniently, the Equation (5) can be described in other expressions;

$$P(k_1, k_2, z) = \frac{2P_E}{\pi w^2(z)} \int_{y=-r_2}^{r_2} \int_{x=D-\sqrt{r_2^2-y^2}}^{D+\sqrt{r_2^2-y^2}} \exp\left(-\frac{2(x^2+y^2)}{w^2(z)}\right) dx dy \quad (6)$$

The $P(k_1, k_2, z)$ is the power collected by the receiving fiber corresponding the parameters k_1 and k_2 . The radial coordinate r is expressed by $\sqrt{x^2 + y^2}$ in Cartesian coordinate system.

Fig. 2 illustrates the overlap area of the reflected light area and the core of the receiving fiber. The overlap area is zero at $x_2 = 0$ (Fig. 1(a)) or $x_1 = 0$ (Fig. 1(b)) and at a very small displacement (blind area) where the jacket of the two fibers blocks the reflected light. As the displacement is increased further, the overlap area increases and thus increases the total power collected by the receiving core. The total power is maxima when the reflected light cone covers the entire receiving core area. After that, the received optical power starts to decay exponentially as the displacement continues to increase. The received optical power is strongly dependent on the core size of the receiving fiber. At inclination angle of 2θ between the transmitting and receiving fibers, the distance x_1 between the sensor probe tip and reflector is given by [4]

$$x_1 = \frac{r_{d1}}{2} (\text{cosec}\theta - 2\sin\theta) \quad (7)$$

From the geometrical analysis of Fig. 1, the distance x_2 is obtained as; $x_2 = x_1 - r_{d3}\sin\theta$ for $r_{d1} < r_{d2}$ (Fig. 1 (a)) or $x_2 = x_1 + r_{d3}\sin\theta$ for $r_{d1} \geq r_{d2}$ (Fig. 1(b)) where $r_{d3} = r_{d2} - r_{d1}$. Therefore, the distance between sensor probe tip and reflector mirror can be summarized as;

$$\begin{aligned} x_2 &= \frac{r_{d1}}{2} [k_2 \text{cosec}\theta + 2\sin\theta(1 - 2k_2)] \quad (r_{d1} > r_{d2}) \\ &= \frac{k_2 r_{d1}}{2} (\text{cosec}\theta - 2\sin\theta) \quad (r_{d1} = r_{d2}) \\ &= \frac{r_{d1}}{2} (k_2 \text{cosec}\theta - 2\sin\theta) \quad (r_{d1} < r_{d2}) \end{aligned} \quad (8)$$

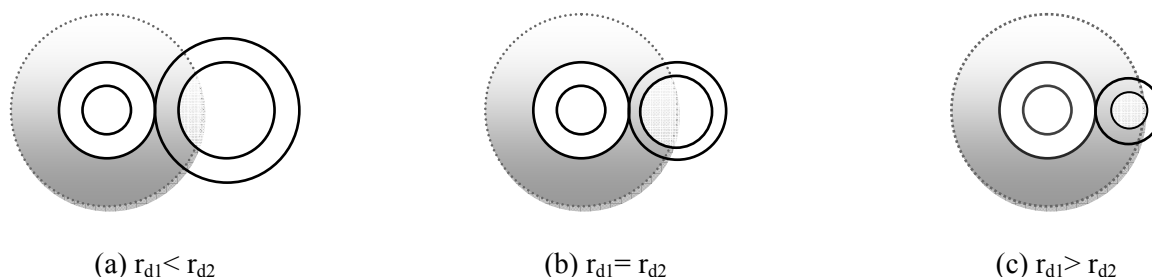


Fig. 2. Overlap area view (a) $r_{d1} < r_{d2}$; (b) $r_{d1} = r_{d2}$; (c) $r_{d1} > r_{d2}$.

3. Simulation and Experiment

The proposed sensor is simulated by using a MATLAB programming. To simplify the analysis, the k_1 values of 0.5, 0.667, 1, 1.5 and 2 are used. The k_2 value is set based on the availability of the fiber in our laboratory. In this simulation, the k_2 values of 0.5, 1 and 2 are used. The wavelength of the laser source λ is set at 594 nm. The numerical aperture values $NA_1 = 0.27$, $NA_2 = 0.32$ and $NA_3 = 0.4$ are used for the core radius of 0.25 mm, 0.5 mm and 0.75 mm, respectively.

To verify the simulated results the FODS is constructed by mounting the transmitting and receiving fibers on the plastic board at angle θ with reference to the normal of the reflector. Separate samples with various fiber diameters and core radius are prepared for angle $\theta = 10^\circ$, 20° and 30° . Light from 594 nm He-Ne laser is modulated by an external chopper at frequency of 200 Hz and launched into the transmitting fiber. The light has an average output power of 3.0 mW, beam diameter of 0.75 mm and beam divergence of 0.92 mrad. The length of transmitting and receiving fiber length is approximately 2 m. The transmitting fiber radiates the modulated light from the light source to the target mirror, while the displacement of sensor probe tip between mirror is controlled by a piezoelectric & driver. The reflective light from target mirror, which is mounted in the bottom of tank, is collected by the receiving fiber whose carries the light into the silicon detector. A lock-in amplifier is connected with the detector to reduce the dc drift voltage due to an ambient light. The initial experiment is carried out by varying the inclination angle between the fibers. The liquid of which the refractive index is measured is filled up in the tank for the LRIS application. The experiment setup of the FODS and LRIS is shown in Figure 3.

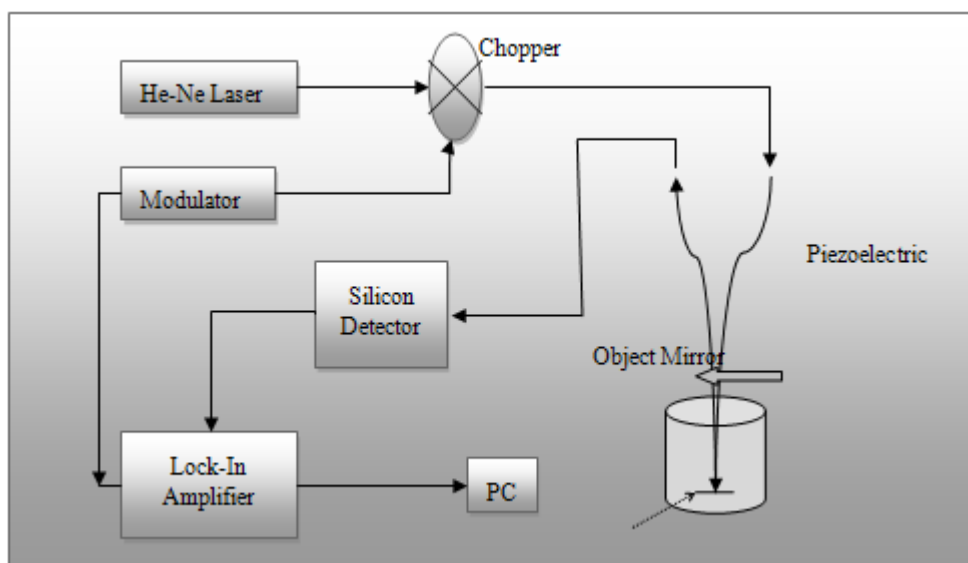


Fig. 3. Experiment setup of the FODS and LRIS.

4. Result and Discussion

Fig. 4 compares the experimental and theoretical plots of the normalized output collected against normalized displacement between probe and reflector with air medium in between. In this study, the ratios k_1 , k_2 , and angle θ are set at 0.667, 0.5, 10° respectively. As shown in the figure, the theoretical curve is in good agreement with the experimental curve, verifying the feasibility of our theoretical model. It is also observed that up to 0.3 (0.5) of separation distance for experimental (theoretical)

curve, light in transmitting fiber would be reflected back into itself and little or no light would be transferred to receiving fiber. This is then referred to as the blind region. As the distance increases, the reflected cone overlaps the receiving fiber core and hence the output intensity increases. This relation is continued until the entire face of receiving fiber is illuminated with the reflected light. This point is called optical peak and corresponds to maximum voltage. As the gap increases beyond this transition region, the intensity drops off following roughly an inverse-square law. The small discrepancy between the theoretical and experimental results is due to the noise sources such as shot noise and thermal noise, which are added to the value of the experimental results and are not calculated in the theoretical analysis.

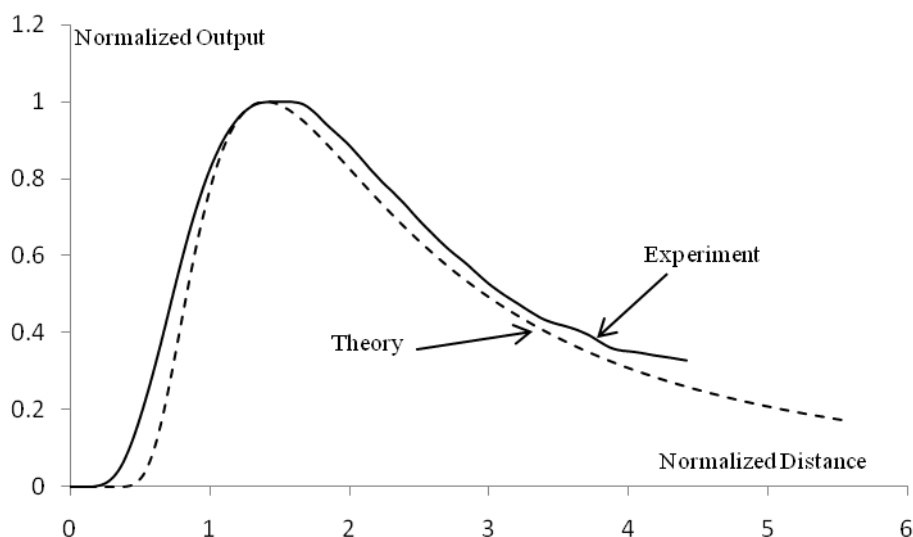
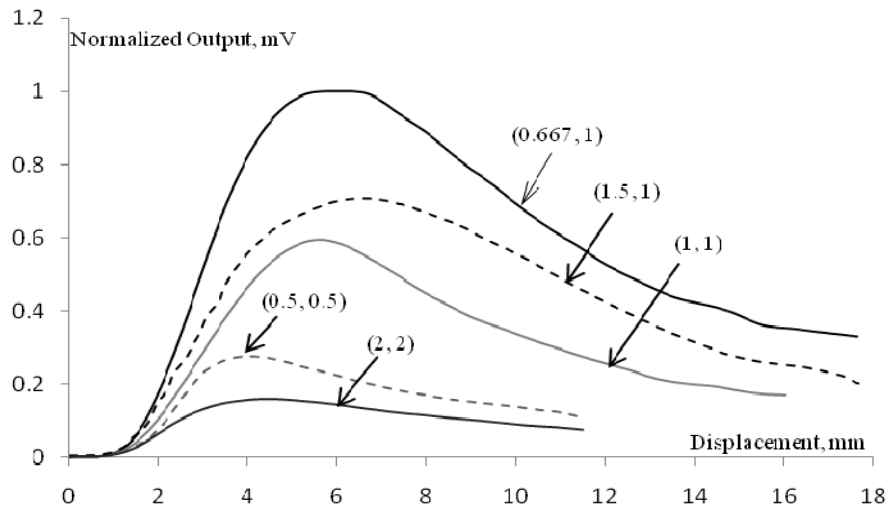
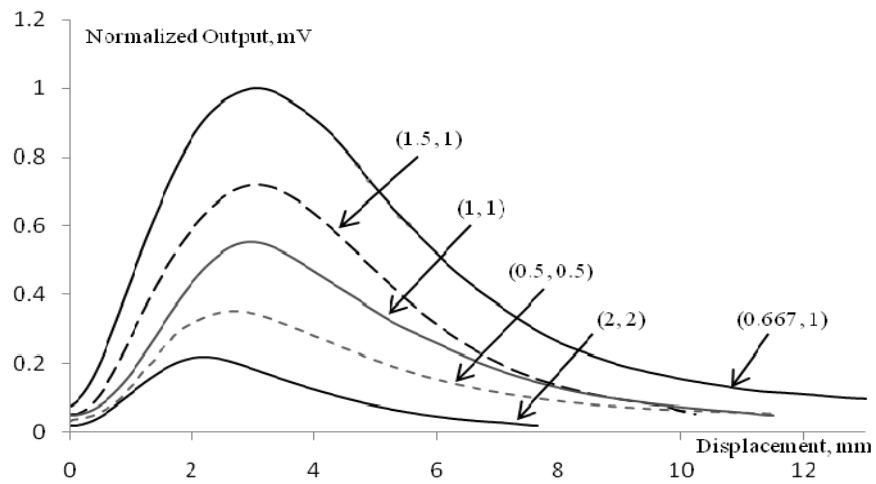


Fig. 4. Comparison between theoretical and experimental curves of the FODS with air medium in between the gap.

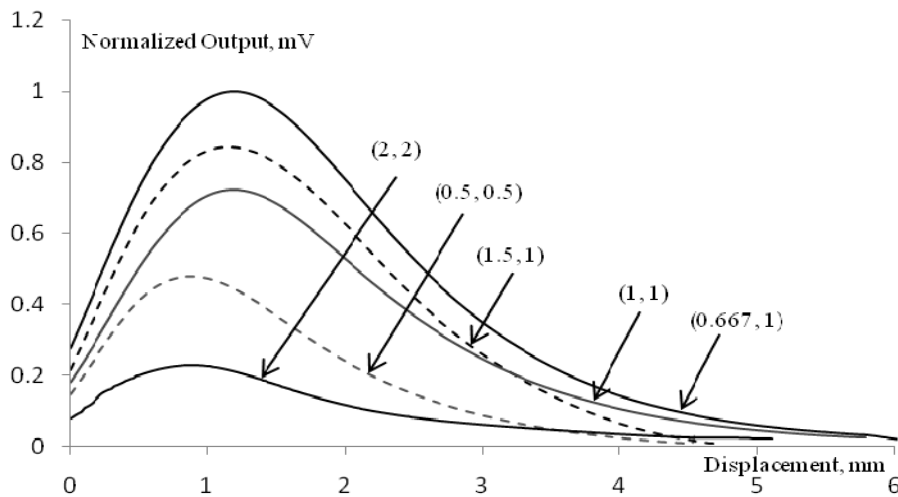
The experiments are also carried out to study the effect of k_1 and k_2 values as well as angle θ on the performance of FODS. Fig. 5 shows the normalized output power against displacement for the FODS at various k_1 and k_2 values as well as the inclination angle. Figs. 5 (a), (b) and (c) show the curves at 10° ; 20° and 30° respectively with an air gap in between the displacement. By comparing the curves in Fig. 5, we understand that the performance of FODS is strongly depended on the fiber core size. The output power collected by receiving fiber is highest when the k_1 and k_2 values are set at 0.667 and 1, respectively. The inclination angle θ of two asymmetrical fiber core is also effected the sensor performance with the bigger inclined angle has a higher output sensitivity with a lower linearity range. Compared to the FODS with zero inclination angle, the sensitivity of the proposed sensor increased by 3.6, 8.5 and 16 times with the inclination angles of 10° , 20° and 30° , respectively. However, the corresponding linear ranges are reduced by 67 %, 55 % and 33 %, respectively. The performances of the proposed FODS are summarized as shown in Table 1. By using the k_1 and k_2 values of (0.667, 1), the maximum sensitivities of 0.2752 mV/ μm , 0.3759 mV/ μm and 0.7286 mV/ μm are obtained at inclination angles of 10° , 20° and 30° , respectively. This sensitivity is higher compared to the previous work by Buchade, et. al [4]. The maximum linear ranges of 10.4 mm, 7 mm and 3 mm are obtained at inclination angles of 10° , 20° and 30° , respectively for the FODS with k_1 and k_2 values of (0.667, 1).



(a) at 10° angle



(a) at 20° angle



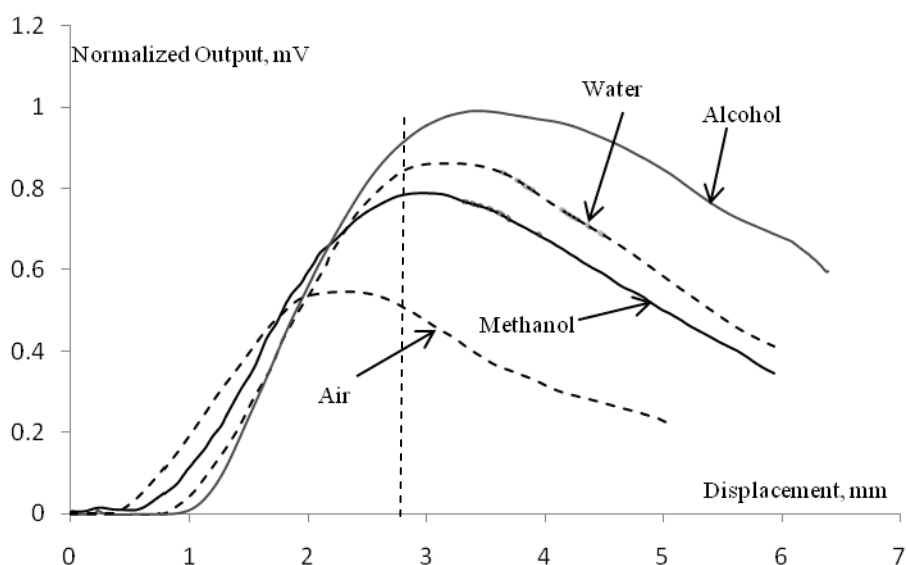
(c) at 30° angle

Fig. 5. The normalized output power against displacement for the FODS at various k_1 and k_2 values with different inclination angles (a) 10°; (b) 20° and (c) 30°.

Table 1. Summary of performances for the proposed FODS.

Methods	Front slopes						Back slopes					
	Sensitivity (mV/ μ m)			Linearity Range (mm)			Sensitivity (mV/ μ m)			Linearity Range		
(k_1, k_2)	10°	20°	30°	10°	20°	30°	10°	20°	30°	10°	20°	30°
(0.5, 0.5)	0.1345	0.1838	0.4761	1.5-3.5	0.4-2.1	0-0.7	0.0223	0.0479	0.1447	4.3-11.5	2.9-8.9	1.5-3.7
(0.667, 1)	0.2752	0.3759	0.7286	1-5.2	0.1-2.8	0-1	0.0675	0.1336	0.3224	6.6-17	3.2-10.2	1.3-4.3
(1, 1)	0.1671	0.2224	0.5528	1.2-4.8	0.2-2.8	0-1	0.0472	0.0823	0.2296	5.6-14.8	3-9	1.2-4.3
(1.5, 1)	0.1885	0.2745	0.6371	1.2-4.8	0.1-2.9	0-1	0.056	0.1155	0.2929	6.8-16	3.2-9.2	1.2-4.3
(2, 2)	0.0645	0.1201	0.1904	1.4-3.5	0.2-2	0-0.8	0.0128	0.0389	0.0885	4.5-11.5	2.4-7.5	1-3

The same experiments are carried out using a liquid as a medium between probe and reflector by fixing the inclination angle at 10°. The results obtained are shown in Fig. 6 for three different liquids; liquid isopropyl alcohol, water and methanol. The isopropyl alcohol, water and methanol have a refractive index n value of 1.3772, 1.333 and 1.329, respectively. In the experiment, the k_1 and k_2 values are fixed at 2 and 2, respectively while the room temperature is set at around 25° to decrease the measurement errors. As shown in Fig. 6, the output power collected by the sensor reduces at small distance (< 2 mm) and increases at a longer distance, with the increment of refractive index. As the refractive index of the medium increases, the angle of emittance decreases hence output power collected decreases because of less overlapping area for displacement smaller than 2 mm. But after this distance density of reflected light increase so output intensity increases. As shown in Fig. 6, the LRIS produces the highest sensitivity at displacement about 3.3 mm. At this distance, the increment of intensity as the refractive index increases is the highest. The output intensity also increases almost linearly as a function of refractive index of the medium.

**Fig. 6.** Normalized output against displacement for the proposed LRIS at k_1, k_2 and angle values of (2, 2, 10°).

5. Conclusions

This paper presents the FODS and LRIS using two asymmetrical inclined transmitting and receiving fibers. A mathematical model based on optical geometry is proposed. The theoretical result of the FODS is in good agreement with the experimental result, verifying the feasibility of this theoretical model. The performance of FODS is strongly depended on the core radius and diameter of transmitting

and receiving fibers as well as the inclination angle. The maximum sensitivities of 0.2752 mV/ μm , 0.3759 mV/ μm and 0.7286 mV/ μm are obtained at inclination angles of 10°, 20° and 30°, respectively for the proposed FODS. Meanwhile, the maximum linear ranges of 10.4 mm, 7 mm and 3mm are obtained at inclination angles of 10°, 20° and 30°, respectively. For the LRIS, the output intensity increases almost linearly as a function of refractive index of the medium at displacement angle of 3.3 mm.

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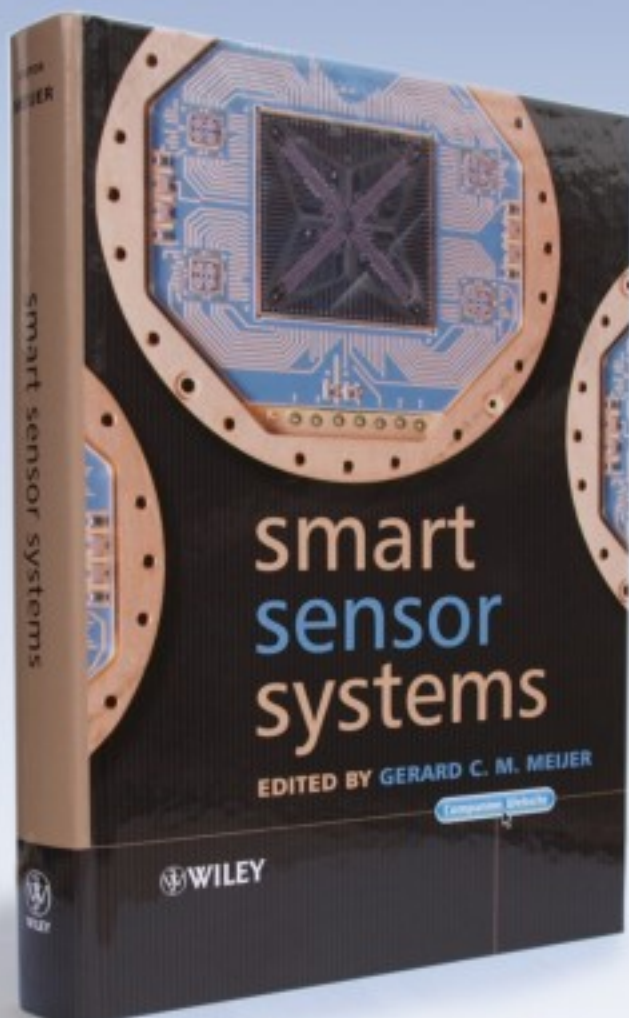
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