

# Theoretical and experimental study of fiber-optic displacement sensor using multimode fiber coupler

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This paper studies the displacement sensor using multimode fiber coupler based on intensity modulation. Fiber coupler used is handmade from plastic optical fiber 1 mm diameter; it has coupling ratio 0.25, excess loss 1.37 dB, and directivity 25 dB. He-Ne laser (632.8 nm) and OPT 101 (Burr Brown) detector is used to detect the change in power-output due to object displacement. The correlation function between power-output and object displacement is analyzed theoretically by Gaussian electromagnetic beam approximation and characterize the dynamic range sensor 4 mm (with linear region 1 mm) and sensitivity is 55.4 55.5  $\mu\text{W}/\text{mm}$ . The experiment shows that the sensor is able to detect object displacement (in front of silvered mirror) accurately in order of 5  $\mu\text{m}$ .

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## 1. Introduction

Fiber optic sensor is commonly used in control and monitoring system for material deformation [1], strain [2], temperature [3], bridge construction [4], and other fields. These fields use the work range of fiber optic displacement sensor.

The mechanisms of fiber optic displacement sensor may be classified into three categories, which are based on wavelength modulation, based on phase modulation, and based on intensity modulation. The first category generally uses fiber Bragg grating and the second one generally uses fiber optic interferometer. Both the first and the second categories have good accuracy but short dynamic range [5]. The third category has lesser accuracy but longer dynamical range; moreover it can be made with lower cost and gives measurements that is easy to interpret [6].

Fiber optic displacement sensor based on intensity modulation can be designed by using the transmission technique, where the coupling loss of power light is measured at two-movable ends of the fiber [7], and the reflection technique, where the coupling loss factor of power light is measured due to the reflection of the moving object [8, 9, 10]. In the reflection technique, the sensor can take form of a pair multi-mode bundled fiber [8], single-mode concentric bundled fiber [9], and multi-mode fiber coupler.

The last study of multi-mode fiber coupler, which uses coupling ratio 0.5, has excess loss 24 dB, dynamic range 2 mm, and sensitivity 6.28  $\mu\text{W}/\text{mm}$  [10]. This paper study use the same multi-mode fiber coupler but lower excess loss and directivity for displacement sensor usage.

## 2. Theoretical analysis

The basic setup of displacement sensor consists of laser, detector, fiber coupler, and target mirror with configuration shown in Fig. 1. The basic principle to measure the displacement of  $z$  is to compare the power light reflected by mirror which is coupled back to port sensing with respect to the power light received by detector  $P_d$  via detection port. The power light received by detector  $P_d$  depends on the distance between sensing port and mirror surface.

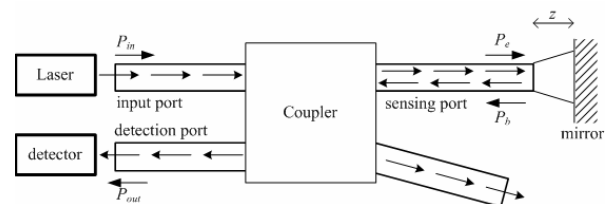


Fig. 1. The basic setup for displacement sensor using multimode fiber coupling. The sensing port is to emitter and also the receiver the light reflected by mirror.

The Gaussian electromagnetic beam is used to analyze the displacement sensor theoretically. It is assumed that firstly, the cross-section surface of the end of fibers at the sensing port is plan and parallel to the mirror surface and secondly the outgoing beam from sensing port is represent by perfectly symmetrical cone with divergence angle  $\theta$  as shown in Fig. 2. The parameters  $a$  and  $W(z)$  in Fig. 2 refer to fiber radius and beam radius respectively; the angle  $\theta$  corresponds to the fiber numerical aperture which is stated as  $NA = \sin(\theta)$  for air medium.

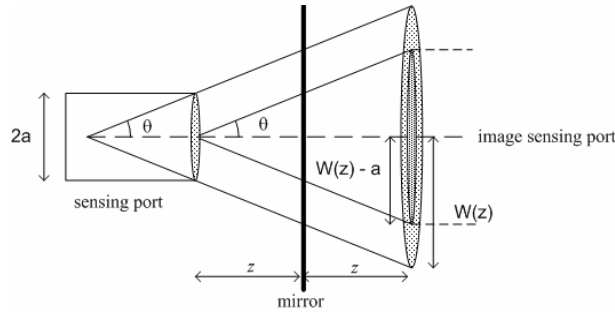


Fig. 2. Evaluating scheme for power light emitted and received by sensing port with image method.

If mirror is parallel to sensing port cross-section, then the power light, which is coupled back to the sensing port, can be determined by

$$P_b = P_t \left( 1 - \exp\left(-\frac{2a}{W(z)}\right) \right) \tag{1}$$

where  $P_t$  is the total power light which is not  $z$ -dependent [11]. It is straightforward from Fig. 2 that

$$W(z) = 2z \tan(\theta) \tag{2}$$

Substitute Equation (2) into (1) and give

$$P_b = P_t \left( 1 - \exp\left(-\frac{2a}{2z \tan(\theta)}\right) \right) \tag{3}$$

where  $c = (2 \tan(\sin^{-1}(NA)))/a$  which makes  $c$  is the constant that is determined by the fiber radius and numerical aperture.

Light transmission process from the source with power light  $P_{in}$  arrive in sensing port (see Fig. 1) and give

$$P_b = P_{in} (1 - c.r.) (10^{-0.4Le} - 10^{-0.4D}) \tag{4}$$

where  $c.r.$ ,  $Le$ , and  $D$  are coupling ratio, excess loss, and directivity of the fiber coupler respectively. If  $z = 0$ , then equation (3) gives  $P_b = P_e$  so  $P_t = 1.15 P_e$ . Thus, equation (3) becomes

$$P_b = 1.15 P_{in} (1 - c.r.) (10^{-0.4Le} - 10^{-0.4D}) \left( 1 - \exp\left(-\frac{2a}{2z \tan(\theta)}\right) \right) \tag{5}$$

The light back-transmission process from the sensing port to detector gives

$$P_d = c.r. P_b (10^{-0.4Le} - 10^{-0.4D}) \tag{6}$$

where  $P_d$  is the power light received by detector. Substitute Equation (6) into (5) yield

$$P_d = c.r. P_b (1 - \exp\left(-\frac{2a}{2z \tan(\theta)}\right)) \tag{7}$$

which is restricted by

$$P_b = 1.15 P_{in} (1 - c.r.) (10^{-0.4Le} - 10^{-0.4D}) \tag{8}$$

Equation (7) is the correlation function of the displacement sensor with multimode fiber coupler.

### 3. Setup experiment

The setup experiment is shown in Fig. 3. It consists of He-Ne laser (Klasse DIN 58126, 632.8 nm, Uniphase) with 1 mW power output, fiber coupler, a planar mirror (front-silvered, 46320, Leybold, a set of displacement equipment with order 5  $\mu$ m (Uniphase), OPT 101 (Burr Brown) detector, and microvoltmeter (Leybold). The fiber coupler used is structured 2x2 and handmade from multimode plastic optical fiber 1 mm diameter (core diameter is 960  $\mu$ m and cladding thickness is 20  $\mu$ m) and 50 cm in length. The fabrication is done with fused method by polishing the fiber. The fiber coupler has coupling ratio 0.25 with tolerance 7%, excess loss 1.37 dB and directivity 25 dB.

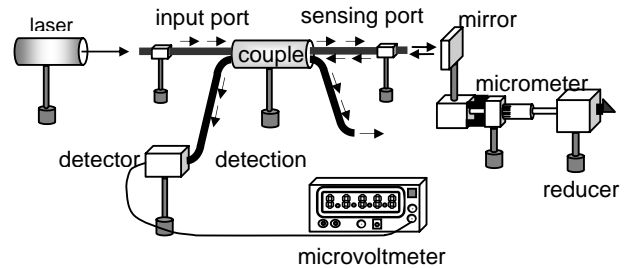


Fig. 3. The setup experiment of fiber optic displacement sensor.

Experiment is conducted by measuring the detector's output voltage with microvoltmeter every 5  $\mu$ m displacement of the mirror away the sensing port. Moving away the mirror can be done by turning the reducer in displacement equipment. Measuring is stopped if displacement of the mirror does not change the detector's output voltage significantly. Detector's output voltage then is converted to laser's power light. The conversion is done by varying the power light from laser, which is can be done by putting a pair of polarizer between laser and the detector and changing its polarization angle. The slope that is given by power light versus detector's output voltage plot is the conversion factor.

### 4. Results and discussion

The conversion of detector's output voltage to laser's power light gives a conversion factor 0.0108 mW/V as shown if Fig. 4. The power light, which detected then is plotted with respect to displacement of the mirror as shown in Fig. 5.

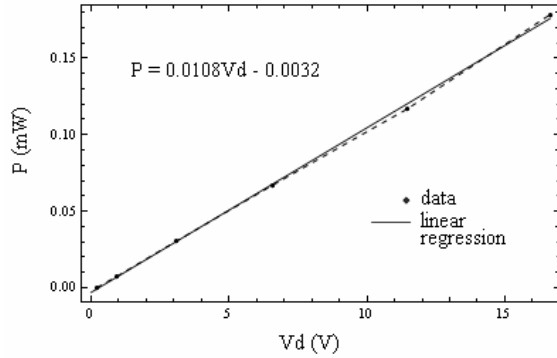


Fig. 4. Linear regression of laser's power light with respect to detector's output voltage.

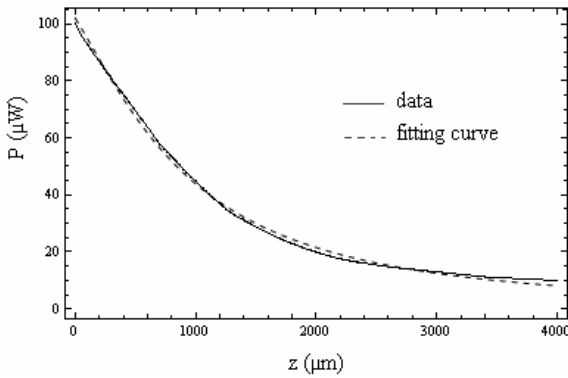


Fig. 5. Plotting power light received by detector with respect to mirror's displacement.

Plot in Fig. 5 shows a very good similarity between the prediction (given by correlation function in Equation (7)) and experiment. Experimental result for  $P_0$  and  $c$  florly are  $118 \mu\text{m}$  and  $1.1 \times 10^{-3}/\mu\text{m}$  respectively. Theoretical prediction for  $P_0$  (given by Equation (8) and substituting  $c.r. = 0.25$ ,  $Le = 1.37 \text{ dB}$ ,  $D = 25 \text{ dB}$ ,  $P_{in} = 1 \text{ mW}$ ) is  $114 \mu\text{m}$ ; and for  $c$  (given by  $2 \tan(\sin^{-1}(NA))/a$  and substituting  $a = 480$ ,  $NA = 0.47$  [12]) is  $2.2 \times 10^{-3}/\mu\text{m}$ . asd

The comparison of  $P_0$  between experimental and theoretical prediction is about 1.7%. As the 7%–tolerance of fiber's coupling ratio is concern, this difference is insignificant. It indicates that the setup experiment is good and the sensor work properly.

The comparison of  $c$  takes 50% difference. This difference is due to the fiber numerical aperture that very much depends on angle  $\theta$ . Angle  $\theta$  theoretically indicates the beam is homogeneous and perfect cone-shape, the shape that is assumed exists in region away from sensing port. But, in experiment the outgoing laser beam from sensing port is Gaussian with paraxial-shape beam. This paraxial-shape beam is on the top of the theoretical cone-shape beam. Since NA theoretical calculation does not use paraxial-shape beam, the 50% difference does make sense. Nevertheless, theoretical analysis that has been done can simplify the correlation function for the sensor.

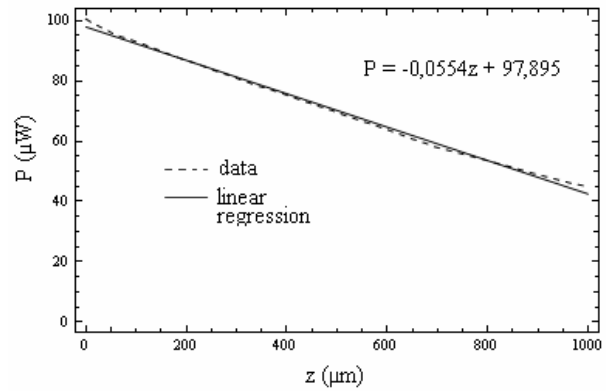


Fig. 6. The linear region of plotting power light received by detector with respect to mirror's displacement.

Fig. 6 shows the linear region of Fig. 6 and it has 1 mm in range. The linear region is the work region of the displacement sensor. This 1 mm-linear region can be considered very wide as the  $5 \mu\text{m}$ -displacement resolution is concern. The slope of the linear region gives the sensitivity of sensor, that is  $55.4 \mu\text{W}/\text{mm}$ , which is more sensitive than the previous study done by [10]. The complete sensor's characteristics are given by Table 1.

Table 1. Characteristics of the sensor.

Parameter	Value
Power source (mW)	1
Displacement resolution ( $\mu\text{m}$ )	5
Dynamic range (mm)	4
Linearity range (mm)	0-1
Sensitivity ( $\mu\text{W}/\text{mm}$ )	55.4

## 5. Conclusion and outlook

Fiber optic displacement sensor using multimode fiber coupler based on intensity modulation has been demonstrated. In general, both theoretical and experimental results agree each other. The difference specifically comes from the numerical aperture fiber which has been known since theoretical calculation uses different shape beam with the one happens in experiment.

Experiment shows very good sensor's sensitivity ( $55.4 \mu\text{W}/\text{mm}$ ). As this sensitivity is gotten from 1 mW incoming power light, the sensitivity would go higher if the incoming is bigger. It is possible to use this setup sensor, with proper incoming power light, to work in nanometer region.

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