

## Bent of plastic optical fiber with structural imperfections for displacement sensor

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An arrangement of bending and structural imperfection in a plastic optical fiber (POF) for a displacement measurement system has been investigated. An evaluation on the output power of the POF caused by the displacement which induced the bending alongside the POF's structural imperfection was determined. The experimental measurement clearly revealed that the sensor exhibited an increasing sensitivity and better resolution for the shorter sensor and more structural imperfection. Additionally, the sensor can be applied for measuring the displacement in the range of 15 mm by means of infrared LED. The maximum sensitivity of 0.2401  $\mu\text{W}/\text{mm}$  and the finest resolution of 4.2  $\mu\text{m}$  were obtained by the sensor length of 6 cm with 3 structural imperfections. The proposed displacement sensor offers a very simple design, high sensitivity and resolution, low fabrication cost and good suitability for large displacement measurements.

**Keywords:** Plastic optical fiber, Displacement sensor, Structural imperfection

### 1 Introduction

The use of fiber optics for sensor technology offers many advantages and becomes very promising for an alternative sensor as compared to the conventional one. The advantages of the fiber optic sensors as compared to the conventional sensors can be distinguished in terms of their sensitivity, selectivity, reversibility, flexibility, accuracy, light weight, and size. In addition, the major advantage of the fiber optic sensors is that they can be designed for measurement of system and remote sensing. Various types of fiber optic sensors have been developed for many measurement purposes, such as to examine strain, stress, displacement, temperature, and pressure<sup>1</sup>. Glass optical fibers (GOFs) and plastic optical fibers (POFs) are then well recognized as the types of fiber optic sensors.

Compared to the GOFs, the POFs perform better in some aspects for a displacement sensor. The POFs provide a large elastic strain range, high fracture toughness, high sensitivity to strain and negative thermo-optic potential coefficients<sup>2,3</sup>. They also give a higher numerical aperture, easier connectivity, lower in cost, and high flexibility<sup>4,5</sup>. Likewise, Young's modulus of the POFs allows wider range of

displacement measurements that are mainly caused by the ability of the sensors to resist higher strains without any damage. Thus, the POFs offer an alternative solution in case of the sensors realization for structural engineering applications. The POFs, however, may generate similar performances with the GOFs, but the POFs only require very low of interrogation and low cost of installation. Likewise, if POFs are compared to random hole optical fibers (RHOFs) and superconducting optical fibers (SOFs), it will be revealed that the POFs have superiority due to their simple structure and low cost consuming. Therefore, the POFs have been investigated for displacement measurements as described in the present paper.

Numerous studies on POFs have been conducted to perform the displacement measurements, for instance Bruno Nilsson *et al*<sup>6</sup>. have applied POF to measure the dynamic surface displacement under the influence of shock wave using LED as the light source, and the LED was then passed through the POF and reflected back into the fiber. They found that the changes of reflected light intensity were proportional to the distance to the surface. A similar device has been reported by Casalicchio *et al*<sup>7</sup>. by means of compensation system based on dual

wavelength approach to generate reference and measurement signals. In their experimental set-up, a dichroic filter was placed at the end of the fiber.

Another approach has been used by Moh Yasin *et al.*<sup>8</sup>; they performed a measurement by means of a multimode plastic fiber bundle with an intensity modulation technique. The sensor was able to measure mirror shifts that was proportional to the output voltage at the probe and having a measurement range of about 1.2 mm. Perrone *et al.*<sup>9</sup> have also developed a system for structural elongation measurement based on POF sensor. Another displacement sensor using POF with multi loops and structural imperfections, having resolution of 50  $\mu\text{m}$  in the range of 40 mm, was presented by Babchenko *et al.*<sup>10</sup>. The sensor's sensitivity was proportional to the additional number of loops and the number of structural imperfections.

There are two main quantities which strongly influence the mechanism of light lost in the POF, i.e. macro bending and micro bending. When the fiber is bent significantly, the macro bending will occur and causes power loss. On the other hand, the micro bending occurs when the bent involves small-scale fluctuations in the fiber axis. The micro bending can also occur with the same effect on the bending of the fiber which has the structural imperfection<sup>11</sup>. It has also been reported by Yung-Chuan Chen *et al.*<sup>12</sup> that the combination effect of bending and elongation led to the power losses in the plastic optical fiber.

In the present paper, we present a simple displacement sensor configuration by using a bent of POF with the structural imperfections at the surface. Instead of using the POF system which was made by Babchenko *et al.*<sup>10</sup>, we introduce a simpler model of lengthened POF with strain and micro bending effects. Therefore, measurement of small displacement with higher resolution can be easily conducted by means of this simple model as an alternative to the previous POF system. An output

power of the POF is based on the mechanism of bending and structural imperfection. The variation of output powers due to the bending and structural imperfection has been examined. This displacement sensor has many advantages, such as much simpler, more effective, higher sensitivity and resolution, and lower cost as compared to another displacement measuring instruments.

## 2 Experimental Set-up

Figure 1 shows the system configuration that was used in measuring the displacement by means of the POF based on a combination of bending and structural imperfection effects. The source of light was the LED infrared (IF-E91A) having a wavelength of 950 nm. The light was directly emitted into the POF and then received by a detector which was connected to the optical power meter (Thorlabs PM100D). Specifically, a step-index specimen of POF was Mitsubishi Rayon SH-4001. Diameter of lining jacket, cladding, and core are 2.2 mm, 1 mm, and 0.98 mm, respectively. A numerical aperture (NA) of the specimen is 0.5.

As shown in Fig. 1, the POF at point A was fixed but point C was placed on translation stage which was moveable by the change of the displacement. The POF was fixed using cyanoacrylate glue. A mandrel with a diameter of 5 mm was also fixed at point B that was exactly in the middle of the POF. When the translation stage is shifted by micro displacement, the position of POF at BC will move to position of BC' and implies some elongation and bending around the mandrel of the fiber. Herein the experiment, the POF length (from A to C) varies with the values of 12 cm, 10 cm, 8 cm and 6 cm. The light from the LED was transmitted via the POF and then received by the detector which was connected to the power meter. The output power was measured for every displacement with an increment of 0.5 mm. The bending and the structural imperfection of the POF

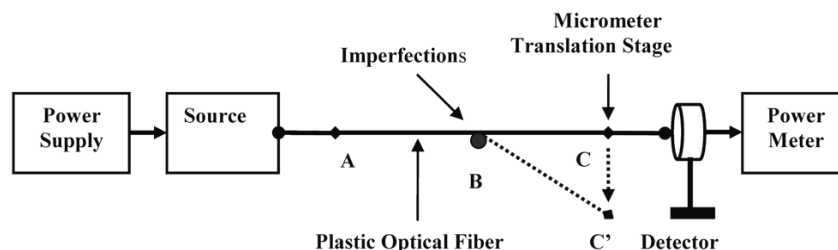


Fig. 1 — Schematic configuration of the POF displacement sensor

are expected to exhibit significantly affects on characteristics transmission of the POF.

The structural imperfections of the POF were created to improve the sensitivity of the displacement measurements. Particularly, the imperfection on the outside of the POF was given to amplify the effects which may take place during micro bending and imply a large reduction in numerical aperture<sup>11</sup>, like as shown in Fig. 2. The structural imperfections were prepared by scraping away the outer surface of the cladding and core in shapes of circle-quarter curves. The width and depth of imperfections were made with the same size and one defect was separated for 1 mm to another one. The depth of imperfection was 0.1 mm. The measurements were performed with variation of structural defects of 1, 2 and 3 on the same fiber at the position of point B near the mandrel.

**3 Results and Discussion**

The experimental investigations were carried out by the POF based on bending and structural imperfection effects. The measurements were conducted at various sensor lengths to determine an optimal result with a consideration of displacement limit at 15 mm from point C to C'. That displacement distance is, however, under threshold of maximum elasticity of the POF, i.e. 10%. Recently, Large *et al*<sup>13</sup>. have reported that the POF had an elastic limit of 10% and showed the POF can resist the strain of more than 30% without any damage. The output power of the POF displacement sensor with the variation of the length is shown in Fig. 3.

Figure 3 shows that the output power varies with the displacement for different length of POF from 6 to 12 cm. The output power decreases by the addition of the displacement. The output power, output power range and linearity of the graph are also changing in accordance with the variations of the length of the

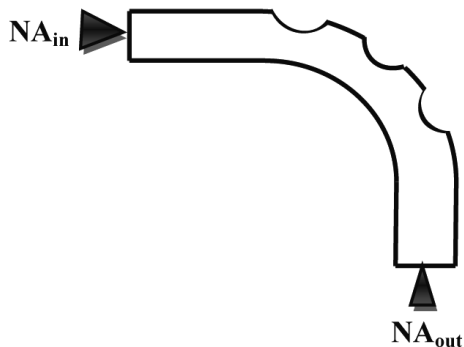


Fig. 2 — POF with the structural imperfection

fiber sensors. The shorter of the fiber sensor is 6 cm shows the highest output power around 5 μW at 0 mm and decreases to around 2.5 μW at 15 mm. Figure 3 also shows clearly the longest fiber sensor and the output power is nearly constant at 1 μW even for the displacement increase up to 16 mm.

The results of the displacement measurements from 0 to 15 mm using the POF with the structural imperfection can be seen in Fig. 4. At the same sensor’s length, it contained four different curves, i.e. 1, 2 and 3 structural imperfections and also one comparison curve representing no imperfection. As shown, it is clearly revealed that the output power is reduced by increasing value of the displacement for with or without structural imperfection. The more the number of the structural imperfections, the smaller the output power it can produce. It is strongly due to the changes of the micro bending that becomes larger as the increasing of the number of the structural imperfections.

The series of data for the displacement measurement can be evaluated by calculating the value of sensitivity and resolution. The sensitivity can be determined by taking the gradient or slope of the graph at a linear displacement range. More precisely, the sensitivity is calculated by Eq. (1):

$$S = \frac{P_{max} - P_{min}}{L_{max} - L_{min}} \dots (1)$$

where  $P_{max}$  is the maximum output power,  $P_{min}$  is the minimum output power,  $L_{max}$  is the maximum displacement and  $L_{min}$  is the minimum displacement.

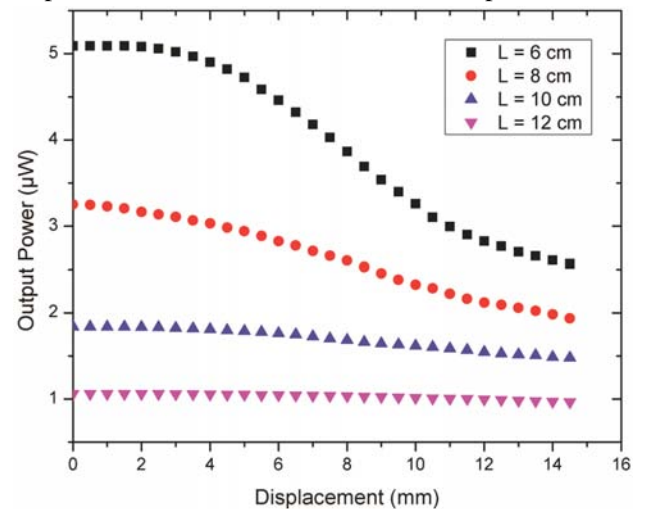


Fig. 3 — Output power of displacement sensor with the variation of the length

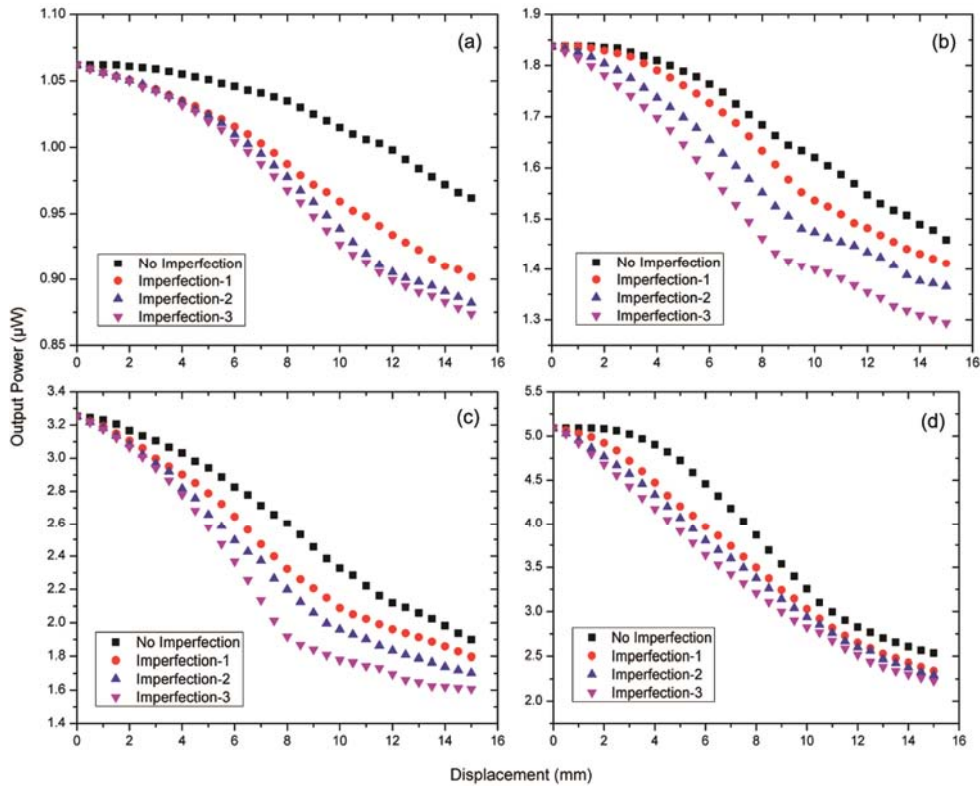


Fig. 4 — Output power of the displacement measurement with the sensor lengths (a) 12 cm,( b) 10 cm, (c) 8 cm and (d) 6 cm

Table 1 — Sensitivities of the fiber optic sensor at the displacement value of 8 mm

Sensor length (cm)	Sensitivity ( $\mu\text{W}/\text{mm}$ )			
	No Imperfection	Imperfection-1	Imperfection-2	Imperfection-3
12	0.0071	0.0127	0.0161	0.0165
10	0.0329	0.0385	0.0378	0.0429
8	0.1140	0.1176	0.1230	0.1354
6	0.1943	0.2234	0.2267	0.2401

After analyzing the data using Eq. (1), the sensitivity of each fiber sensor length at a displacement value of 8 mm is presented in Table 1.

From the data given in Table 1, it indicates that the increasing sensitivity is mainly due to the addition of the structural imperfection. It is found that the highest sensitivity to be  $0.2401 \mu\text{W}/\text{mm}$  for the length of 6 cm and 3 imperfections.

The resolution, by definition, is the smallest value that can be detected by the displacement measuring instruments. The resolution can be calculated using Eq. (2):

$$R = \frac{\Delta P}{2} \dots(2)$$

where  $\Delta P$  is the smallest scale that can be detected by the power meter and  $S$  is the sensitivity. Assuming  $\Delta P$  is  $0.001 \mu\text{W}$ , and then the resolution can be calculated based on the sensitivity data.

Having performed the data analysis on the displacement measurement, we can safely say that there exist a better resolution for the shorter of the sensor and more of the presence of the structural imperfections. The best resolution, i.e.  $4.2 \mu\text{m}$ , is obtained for the sensor with the length of 6 cm and 3 imperfections. The results clearly revealed that this displacement measurement system can perform higher sensitivity and resolution as compared to other sensors.

#### 4 Conclusions

We have proposed the displacement measurement method using the bent of POF with structural imperfections which is really simple, low cost, high resolution and high sensitivity. Two of the most predominant factors to improve the sensitivity and resolution of measurement are the number of structural imperfections and the length of the fiber sensor. When the fiber sensor becomes shorter and the structural imperfections get an extra amount, the higher the sensitivity and the better the resolution can be achieved. The highest sensitivity is obtained at  $0.2401 \mu\text{W}/\text{mm}$  and the best resolution of  $4.2 \mu\text{m}$  for the sensor with 6 cm in length and 3 imperfections. Hence, this displacement measurement technique is very useful for structural health monitoring applications involving larger displacements.

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