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Utilization of Optical Fibers as Displacement Sensors

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Abstract. *An experiment examined micrometer shifts in optical fibers to understand sensor characteristics: range, linearity, sensitivity, and resolution. Findings showed voltage output decreases with fiber length. The fiber coupler sensor's range was 2 mm, and the fiber bundle sensor's was 25 mm.While not perfectly linear, the study identified operational ranges using* $y = ax + n$*. The fiber bundle had two linear regions: Front Linear (0.2-1.6 mm) with* $R^2 = 0.9918$ *and Rear Linear (2.3-8.3 mm) with* $R^2 = 0.977$*. The fiber coupler's linear trend spanned 0.3-2.1 mm with an* R^2 *of 0.944. Sensitivity was 4668.5 V/mm (front) and 780.91 V/mm (rear) for the fiber bundle, and 215.79 V/mm for the fiber coupler. Resolution was 0.0107 µm (front), 0.0640 µm (rear) for the fiber bundle, and 0.2317 µm for the fiber coupler. These findings shed light on optical fiber shift sensor parameters.*

Keywords : *optical fiber, displacement sensor, fiber coupler, fiber bundle*

BACKGROUND

The use of optical fibers as sensors has rapidly evolved and found numerous significant applications across various fields such as healthcare, environmental monitoring, and industry. Traditionally known for their role in communication systems as transmission media, optical fibers are now also utilized as sensor components. Advantages of optical fiber sensors include low cost, high sensitivity, and remote sensing capability. Displacement sensors utilizing optical fibers can be constructed using fiber bundles and fiber couplers.

A fiber bundle consists of multiple optical fibers combined at one end, used as a displacement sensing element. In contrast, a fiber coupler is a combination of two optical fibers joined in the middle, featuring one input, one sensing output, and one unused parallel output. The working principle of an optical fiber-based displacement sensor involves detecting changes in the intensity of light reflected from a moving object (such as a mirror), which is then converted into an output voltage by a detector.

This study aims to examine the characteristics of an optical fiber-based displacement sensor, including its range, linearity, sensitivity, and resolution. The experiment involved measuring micrometer shifts in optical fibers and analyzing the output voltage to understand these sensor parameters. The findings indicated that the output voltage decreases as the fiber length increases. The fiber coupler sensor exhibited a range of 2 mm, while the fiber bundle

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sensor had a range of 25 mm. Although not perfectly linear, the study identified operational linear ranges for both types of sensors.

With the growing demand for more efficient and precise sensors in various technological applications, this research makes a significant contribution to the understanding and development of optical fiber-based displacement sensors. The results of this study not only enrich the scientific literature but also pave the way for broader practical applications in the future.

BASIC THEORY

The use of optical fiber as a sensor has found many applications in important fields such as health, the environment and industry. It turns out that optical fiber is not only useful in communication systems, but is also useful as a sensor component. This is because the use of optical fiber as a sensor has many advantages, including low cost, high sensing sensitivity, and it can also be controlled over long distances. Shift sensors can be built using fiber bundles and fiber couplers. A fiber bundle is a combination of two optical fibers bundled at one end which is used as a shift sensing element, in other words close to the mirror. Meanwhile, a fiber coupler is a combination of two optical fibers which are combined in the middle of the two optical fibers so that there will be one input output, one sensing output, one output and another output which is parallel to the sensing output which is not used.

Optical fiber is an electromagnetic wave transmission medium made from transparent materials such as silica, glass or plastic. The principle of perfect reflection (total internal reflection) by utilizing the difference in refractive index between the core or cladding layers. The use of optical fiber as a sensor has many advantages, including low cost, high sensing sensitivity, and it can also be controlled over long distances. (Samian, 2023).

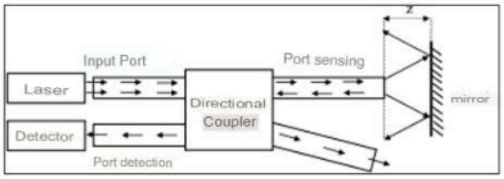


Figure 1. Fiber coupler design as a shift sensor

The working principle of a fiber coupler as a shift sensor is as follows. The sensing port of the fiber coupler in Figure 4.2 acts as both a transmitter and receiver of light rays reflected from an object in the form of a flat mirror. The mirror shift (z) will cause a change in the light intensity received by the sensing port. Changes in light intensity can be detected through the detection port and represented through the detector output voltage. Because the source used is a laser which has an output beam

Gaussian in shape, then the analysis of changes in optical power at the sensing port due to mirror shift is carried out using a Gaussian beam approach. The principle of object shift detection (z) is to detect changes in the intensity or optical power of reflected light from an object that is coupled back to the sensing channel (Pb). Through the coupling process in the fiber coupler, changes in optical power are detected through the optical power of the light received by the detector (Pd). If the light beam is Gaussian, the relationship between Pd and z is expressed by the following equation:

$$P_d = P_d \left(1 - \exp\left(-\frac{2}{(cz+1)^2}\right)\right)$$

with c = (2 tan (sin-1 (NA))/a while NA and a are the numerical window and optical fiber core radius respectively. Po is expressed by the following equation:

$$P_o = 1{,}15cr(1-cr)(10^{-0{,}1L_e} - 10^{-0{,}1D})^2 P_{in}$$

provided that cr, Le and D are the fiber coupler parameters used. The equation shows that the relationship between Pd is not linear with respect to z. However, experimentally it can still be found that some of the regions are described by linear equations. The characteristics of a displacement sensor consist of range, linear range, sensitivity, and resolution. Range is the furthest shift range that the sensor can sense. The linear area is the sensor's working area, namely the shift range which has a linear relationship with the sensor output parameters, in this case the detector output voltage. Sensor sensitivity is the ratio between the sensor output parameters and the sensing parameters. Sensor sensitivity is obtained from the slope of the linear graph between the detector output voltage and displacement. Resolution is the smallest shift that the sensor can perceive.

a. *Fiber bundles* As a Shift Sensor

The working principle of object shift detection using fiber bundles is almost the same as using a fiber coupler as a sensor, which is based on modulating light intensity using reflection techniques. The shift of an object in the form of a mirror is detected through changes in the intensity of reflected light from the mirror received by the fiber bundle. This mechanism is shown in Figure 2. The fiber bundle used as a shift sensor in Figure 2 is a pair bundle probe type, namely an optical fiber that functions as a light emitter (optical fiber 1) and another optical fiber functions as a light receiver (optical fiber 2). From figure 2 it can be understood that if the mirror shifts, the intensity of light entering the optical fiber 2 also changes. If optical fiber 2 is connected to an optical detector, changes in light intensity (the output of the optical detector is an electrical voltage) can be read or measured. With

Thus, object displacement is detected through changes in the intensity of light entering the optical fiber receiver or changes in the output voltage of the optical detector.

b. *Fiber couplers* As a Shift Sensor

One of the functions of a fiber coupler is as a light beam divider. Therefore the fiber coupler can be applied as a shift sensor. Based on intensity modulation, the working principle of the sensor uses reflection techniques. Intensity modulation in question is a shift in an object that is responded to by changing the intensity of light hitting the object. The technique used is called a reflection technique because the change in light intensity felt by the fiber coupler is a result of the reflection of a shifting object. The fiber coupler design as a shift sensor is shown in the image below

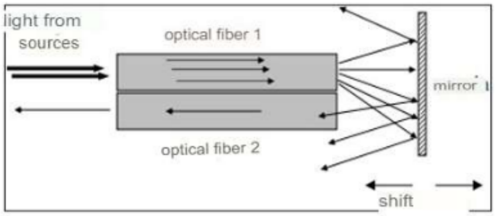


Figure 2. Scheme of receiving reflected light from a mirror

EXPERIMENTAL METHODOLOGY

1. Tools and Materials

Tools and materials used in Lasers, Detectors, Input ports, Detection ports, Sensing ports, Mirrors, Position micrometers, Microvoltmeters.

2. Practical Procedures

The experimental procedure for using fiber couplers and fiber bundles as displacement sensors is as follows. The experiment began by arranging the experimental equipment according to Figure 3 for a shift sensor using a fiber coupler and Figure 4 for a shift sensor using a fiber bundle. After all the experimental equipment is activated, place the sensor probe (for fiber coupler or fiber bundle) adjacent to the mirror with the sensor probe positioned perpendicular to the mirror. Note the detector output voltage read by the voltmeter (microvoltmeter) every time the mirror is shifted by 100□m away from the mirror. The mirror shift is carried out until the shift does not result in a significant change in the detector output voltage. Repeat the experiment three times. From this repetition, the detector output voltage measurement error will be obtained(□V).

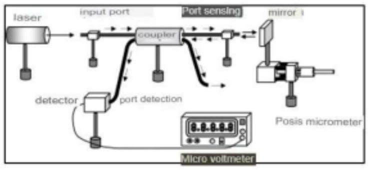


Figure 3. Shift sensor using fiber coupler

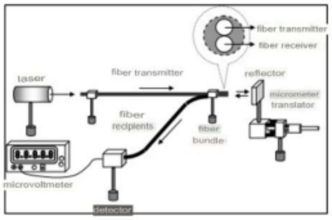


Figure 4. Shift sensor using fiber bundle

RESULTS

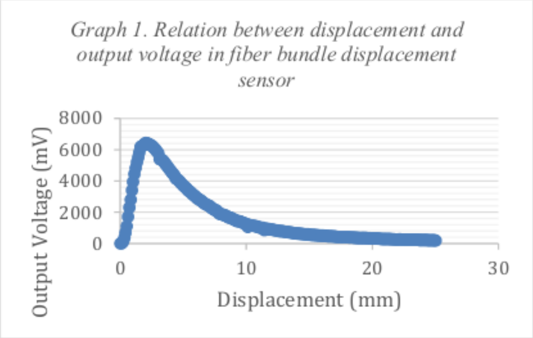
1. Shift Sensor with Fiber Bundle

a. Reach

From experiments carried out with groups, a range of up to 25 mm was obtained. In this shift, a graph has been obtained that tends to be linear and continues to decrease in value.

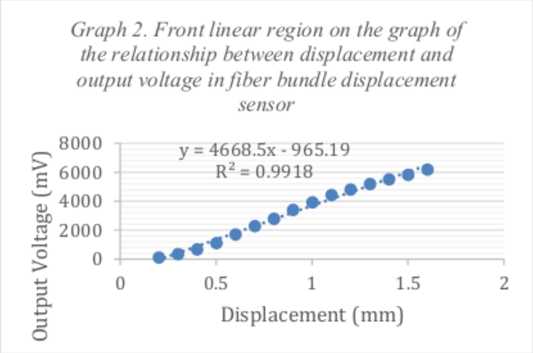
b. Linear Regions

The observation data is graphed to get the linear part of the graph. The data shown in the following graph is the relationship between displacement (mm) and output voltage (mV) in the fiber bundle.



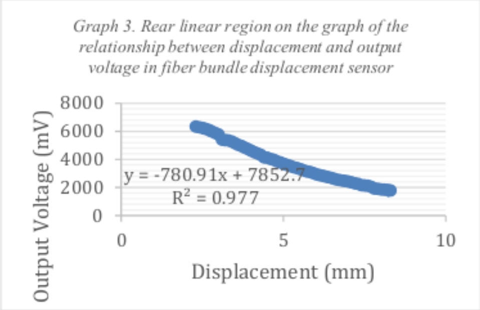
Graph 1. Relation between displacement and output voltage in fiber bundle displacement sensor

From the results of the graph cut, the linear part of the previous graph is obtained and two linear areas are obtained, namely the front linear area and the back linear area with their respective best performance intervals taking into account the R value. The trend in the front linear area is shown by the interval 0.2-1.6 mm on the x-axis, it is found that R^2 is 0.9918



Graph 2. Front linear region on the graph of the relationship between displacement and output voltage in fiber bundle displacement sensor

Then for the Rear Linear Region trend shown by the interval 2.3-8.3 mm on the x-axis, the R^2 value is 0.977.



Graph 3. Rear linear region on the graph of the relationship between displacement and output voltage in fiber bundle displacement sensor

c. Sensitivity

The sensitivity of the sensor, the value can be obtained using the linear regression equation that has been obtained.

Front Linear Region Sensitivity

$y = ax + n \Rightarrow y = 4668.5x - 965.19$

The sensitivity value can be taken from the value "a", namely 4668.5 V/mm.

Rear Linear Region Sensitivity

$y = ax + n \Rightarrow y = -780.91x + 7852.7$

The sensitivity value can be taken from the value "a", namely -780.91 V/mm.

d. Resolution

Resolution (r) can be obtained by dividing the accuracy value of the output voltage measurement (ΔV) by the sensitivity value (s) of the sensor

First, you need to do calculations to get ΔV in the following way:

$\Delta V = 0.5 \times s\text{mallest scale}$

$\Delta V = 0.5 \times 0.1$

$\Delta V = 0.05 mV$

Second, the resolution value (r) can be obtained as follows:

Front Linear Region Resolution

$\text{Resolution}(r) = \Delta V/\text{Sensitivity}(s)$

$\text{Resolution}(r) = 0.05 / 4668.5$

$\text{Resolution}(r) = 0.0107\ \mu\text{m}$

Rear Linear Region Resolution

$\text{Resolution}(r) = \Delta V/\text{Sensitivity}(s)$

$\text{Resolution}(r) = 0.05 / 780.91$

$\text{Resolution}(r) = 0.0640\ \mu\text{m}$

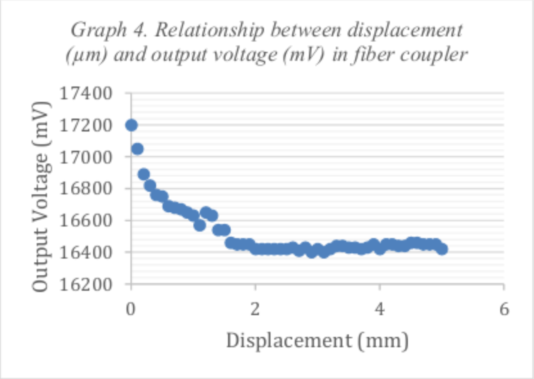
2. Measurement Sensor with Fiber coupler

a. Reach

From experiments carried out with groups, a range of up to 2 mm was obtained. In this shift, a graph has been obtained that tends to be linear and continues to decrease in value.

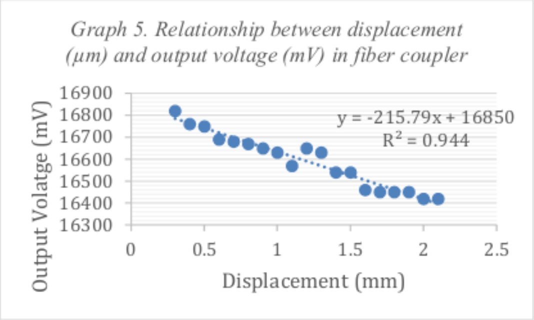
b. Linear Regions

The observation data is graphed to get the linear part of the graph. The data shown in the following graph is the relationship between displacement (µm) and output voltage (mV) on the fiber coupler.



Graph 4. Relationship between displacement (µm) and output voltage (mV) in fiber coupler

From the results of the graph cut, the linear part of the previous graph is obtained. The linear trend is shown by the interval 0.3-2.1 mm on the x-axis, obtained R^2 is 0.944.



Graph 5. Relationship between displacement (µm) and output voltage (mV) in fiber coupler

e. Sensitivity

The sensitivity of the sensor, the value can be obtained using the linear regression equation that has been obtained.

$y = ax + n \Rightarrow y = -215.79x + 16850$

The sensitivity value can be taken from the value "a", namely 215.79 V/mm

f. Resolution

Resolution (r) can be obtained by dividing the accuracy value of the output voltage measurement (ΔV) by the sensitivity value (s) of the sensor

First, you need to do calculations to get ΔV in the following way:

$\Delta V = 0.5 \times \text{smallest scale}$

$\Delta V = 0.5 \times 0.1$

$\Delta V = 0.05 mV$

Second, the resolution value (r) can be obtained as follows:

$\text{Resolution}(r) = \Delta V / \text{Sensitivity}(s)$

$\text{Resolution}(r) = 0.05 / 215.79$

$\text{Resolution}(r) = 0.2317\ \mu m$

DISCUSSION

In the practical report on the micrometer shift in an optical fiber that has been carried out, there are several things that can be analyzed. One of them is the characteristics of the shift sensor, which include range, linear range, sensitivity and resolution. The resulting graph shows that the two graphs are similar, with the difference being that the initial part of the fiber bundle has low tension. The farther the distance the beam must travel, the voltage value will decrease exponentially. This brings us to the first characteristic of shift sensors, namely range. Range is the shift range until there is no change in the output voltage. In this experiment, the reach of the fiber coupler sensor was 2 mm, while the reach of the fiber bundle sensor was 25 mm.

As a displacement sensor, the relationship between output power variables must be linear. Meanwhile, the graphic form presented is not completely linear. This linear area shows the effective working area as a shift sensor. Linear area testing is carried out by selecting data that is assumed to be the most linear compared to the others. The linear area on the graph is the area where the data is estimated to be linearly related following the equation $y = ax + n$; where m is the slope / gradient. From the results of the graph cut, the linear part of the previous graph is obtained and two linear regions are obtained for the fiber bundle, namely the Front Linear Region and the Back Linear Region with their respective best performance intervals taking into account the R value. The trend in the front linear region is shown by the interval 0.2-1 .6 mm on the x-axis, we get an R^2 value of 0.9918. Then for the Rear Linear Region trend shown by the interval 2.3-8.3 mm on the x-axis, the R^2 value is 0.977. Meanwhile, for the fiber coupler, the linear trend is shown by the interval 0.3-2.1 mm on the x-axis, the R^2 value is 0.944.

The linear area graph created then takes us to the next characteristic, namely sensitivity. Sensitivity is the slope value of the line equation that was searched for earlier. So, the sensitivity value of the front and back fiber bundles is 4668.5 V/mm respectively. and 780.91 V/mm. Meanwhile, the sensitivity value of the fiber coupler is 215.79 V/mm. One more sensor characteristic, namely resolution. Resolution is the value of the measurement error quotient (ΔV) with sensitivity. The sensor resolution values obtained for the front and rear fiber bundles were 0.0107 µm and 0.0640 µm respectively. Meanwhile, for the fiber coupler, a resolution of 0.2317 µm was obtained.

CONCLUSION AND SUGGESTION

From the Experimental that has been carried out, for measuring sensors with fiber bundles, a range of 25 mm is obtained, the range of the front linear area at intervals0.2-1.6 mm and the rear linear area ranges at intervals of 2.3-8.3 mm, sensitivity is 4668.5 V/mm for the front linear area and 780.91 V/mm, and resolution is 0.0640 µm. Whereas forThe measurement sensor with a fiber coupler obtained a range of 2 mm, a linear area range at intervals0.3-2.1 mm, sensitivity of 215.79 V/mm, and resolution of 0.2317 µm. Ensure that the output voltage on the shift sensor with a fiber coupler has a maximum value when the fiber coupler tip touches the mirror and ensure that the output voltage value always decreases when the micrometer is rotated to move the fiber coupler tip away from the mirror. Apart from that, it also ensures that the laser is aimed at the end of the fiber coupler so that the output voltage can be read

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