Fiber optic angle sensor based on flat and concave mirror using a multimode fused coupler

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A simple fiber optic displacement sensor (FODS) is proposed and demonstrated for angle measurement. The proposed sensor utilizes a multimode fused coupler as a probe as well as a flat or concave mirror as the target. For the flat mirror, the highest sensitivity and the best resolution is obtained at 0.114 mV/° and 71 mrad, respectively; whereas the highest sensitivity and the best resolution that is attainable when the concave mirror is used are 0.40 mV/° and 2.1 mrad, respectively. The simplicity of the design, high degree of sensitivity, dynamic range and the low cost of the fabrication make it suitable for industry and research applications.

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1. Introduction

The measurement of angular displacements (or inclinations) is very important in many fields, either in industry or research. For example, in industry it is used to control the direction of cars, the kinematics of robot arms, the tilt angles of aircrafts, etc [1-2]. Moreover, this kind of measurement can be integrated into precision rotation stages to control the angular positioning of the optical and/or mechanical components. Many techniques have been proposed for the angular displacements measurement such as interferometric and triangulation methods. The first method is normally based on the Michelson principle with a mirror in the measuring arm having an angular movement [3-4]. These sensors can measure a small range of angular displacements very precisely, but having limitations for their integration in miniature mechanical systems. The triangulation method is based on the light transmitted [5] or reflected [6] by a mirror. In the case of miniaturization of these kind of sensors, they can be fabricated using conventional [5] or silicon-based micro-fabrication techniques [7]. Whatever the choice of fabrication is, it is difficult to have a miniature system with high resolution and long range. The sensor precision remains low and the range is too small.

Recently, fiber optic displacement sensors (FODSs) have been demonstrated for various applications [8-12]. In this paper, a simple yet accurate angle measurement system using a simple reflective FODS is proposed and demonstrated. The proposed sensor utilizes a multimode fused coupler as a probe as well as a flat and concave mirror used subsequently as the target to perform accurate measurements in the micro-radian range for angle measurement.

2. Experimental setup

The experimental setup of the proposed micro-angle measurement based on the reflective fiber optic displacement sensor is given in Fig. 1. The setup consists of a yellow He-Ne laser operating at 594 nm as a signal source and a 1.0 meter long multimode fused coupler. In this demonstration, a flat and a concave mirror each with a diameter of 2.5 cm are used to provide the necessary reflection that will be captured by the receiving fibers. The light source used is a He–Ne yellow laser (594 nm) which is chopped using a mechanical chopper at 113 Hz as to avoid the harmonics from the line frequency which is about 50 to 60 Hz. The reflected optical signal is detected by the silicon photodiode (818 SL, Newport) and the electrical signal is then fed into the lock-in amplifier (SR-510, Stanford Research System) together with the reference signal of the mechanical chopper. The output result from the lock-in amplifier is then connected to a computer through a RS232 port interface and the signals are processed using Delphi software. The mirror is fixed on a rotation stage that can be moved with a 1° resolution at a distance of 1.5 mm, 2.0 mm and 2.5 mm.

As shown in Fig.1, the output light from the mechanical chopper is launched into leg 1 of the fused coupler. The output powers at legs 3 and 4 are divided based on the coupling ratios. For the 50:50 coupler, the output power will be divided equally. However, the total power of legs 3 and 4 are not exactly the same as that of leg 1 due to insertion loss of the fused coupler. Leg 4 of the coupler can be used to monitor the power coupling ratio of the fused coupler. The reflected output from the mirror then enters back into leg 3 and is splitted accordingly by the coupling of the fused coupler and detected at leg 2. The output light is then sent into the silicon photo-detector which is connected to the lock-in amplifier for processing. In this experiment, the angular variation of the mirror is done in steps of 1°.

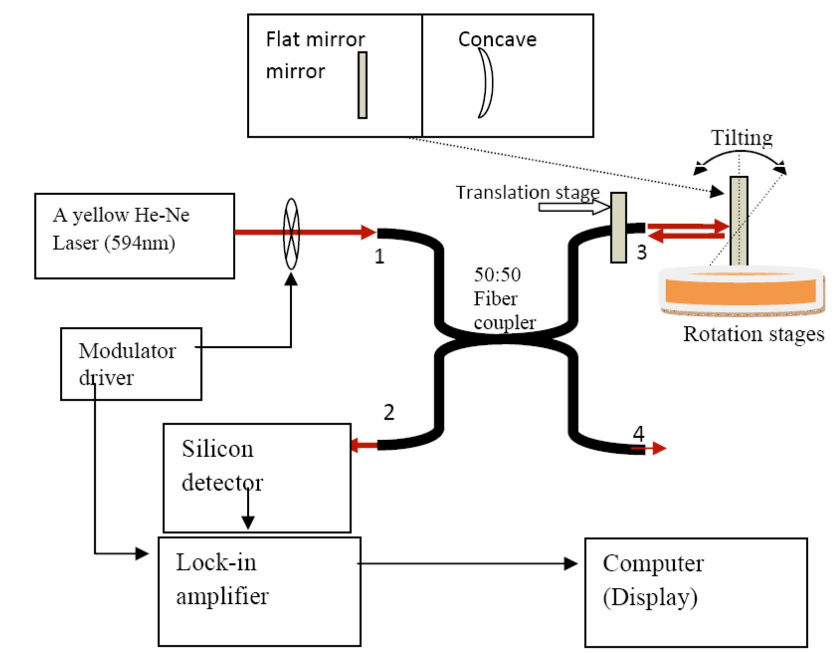


Fig. 1. Experimental setup for fiber optic angle sensor using a fused coupler probe with flat or concave mirror.

3. Results and discussion:

Fig. 2 shows the output voltage as a function of flat mirror angle for the 50:50 coupler splitter with three different probe distances which are l = 1.5 mm, 2.0 mm and 2.5 mm. In this experiment, the flat mirror is tilted to the left and right while maintaining its' perpendicularity to the probe. From this figure, the lowest output voltage is demonstrated at l = 2.5 mm whereas the distance of 1.5 mm gives highest output voltage for all angle of measurements. When the angle is increased, the measured intensity of the reflected light grew almost linearly as manifested after the dark zone region. This region is called the front slope whereby the measured intensity is proportional to the extended angle within this transition region. The measured error for this sensor is 0.047 mV.

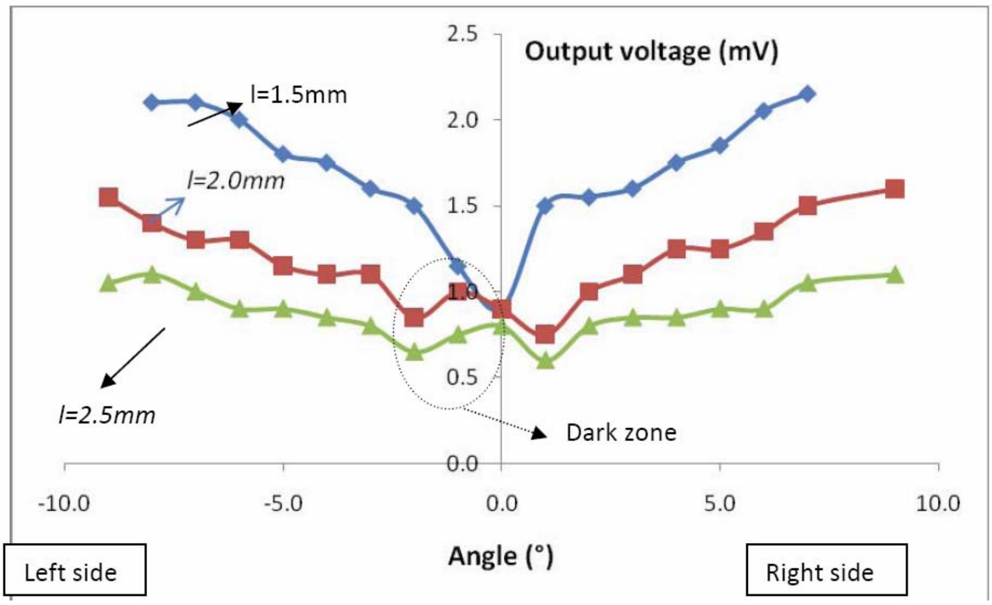
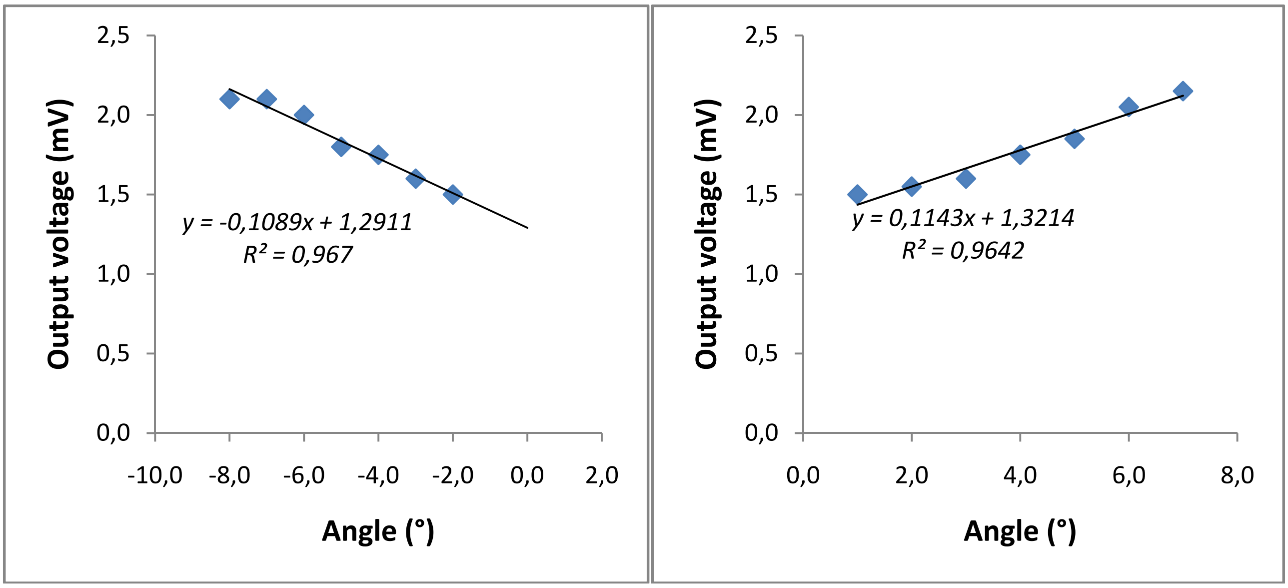


Fig. 2: Output voltage as a function of angle for flat mirror.

The sensitivity of the sensor is determined by the slope of the curves in the linear range. As indicated in Fig. 3a and b, the sensitivity is found to be 0.109 and 0.114 mV/° for the left and right side, respectively. The performance evaluation of the sensor was carried out by tilting the flat mirror sideways from 0 to 8° to the right and left side at *l* = 1.5 mm. This is then repeated with a distance of 2.0 and 2.5 mm from the fused coupler probe. The results are summarized in Table 1.



(a) (b)

Fig. 3. The liner range for the fiber optic angle sensor at the (a) left and (b) right side of the probe with a distance of 1.50 mm.

Table 1. The performance of the fiber optic angle sensor using flat mirror at different probe distances.

Parameter	Left side			Right side		
	l=1.5mm	*l=2.0mm*	*l=2.5mm*	*l=1.5mm*	*l=2.0mm*	*l=2.5mm*
Sensitivity (mV/°)	0.109	0.085	0.064	0.114	0.086	0.044
A linear range (°)	2-8	2-9	2-8	1-7	2-9	2-9
Linearity (%)	98	98	97	98	98	95
Resolution (°)	0.43	0.55	0.73	0.41	0.55	1.07
Resolution (mrad)	7.5	9.6	12.7	7.1	9.6	18.7

Fig. 4 illustrates the output voltage of the lock-in amplifier against the angle at different distances using concave mirror. The distance is varied from 1.5 to 2.5 mm. It is observed that the output voltage is maxima at zero degree before reducing to the minimum value with the increase in the angle. The performance of the fiber optic angle sensor using concave mirror at different probe distances are summarized in Table 2. For the concave mirror, the highest sensitivity and the best resolution are found to be 0.4 mV/° and 0.14 mrad, respectively. This performance is observed at the probe distance of 1.5 mm and is similar with the performance on the left side. The differences are due to the error in the alignment of the probe centre.

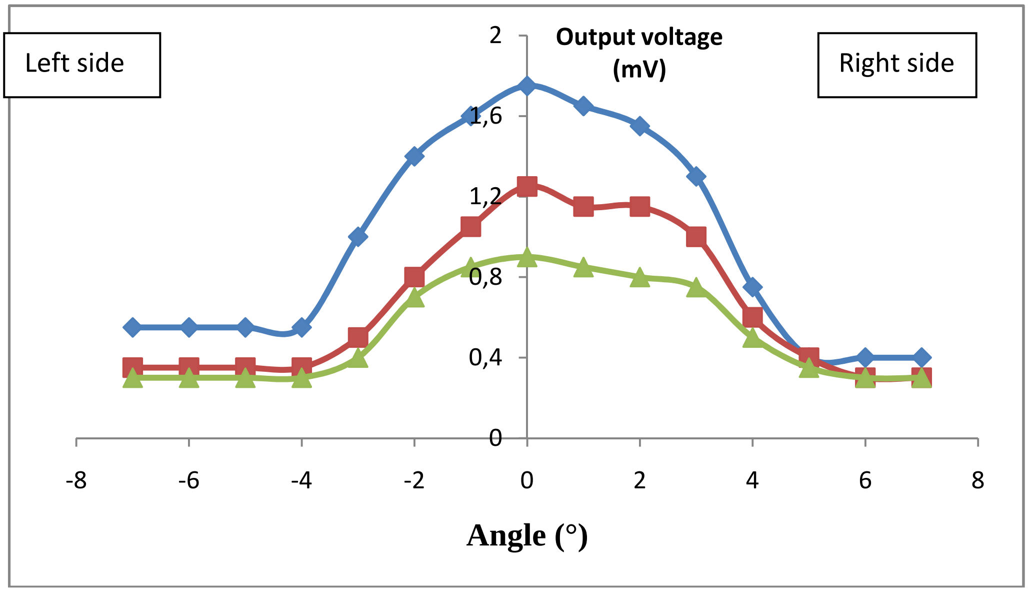


Fig. 4. Output voltage as a function of concave mirror angle.

Table 2: The performance of the 50:50 fused fiber optic angle sensor using concave mirror at different probe distances (l).

Parameter	Left side			Right side		
	l=1.5mm	***l=2.0mm***	***l=2.5mm***	***l=1.5mm***	***l=2.0mm***	***l=2.5mm***
Sensitivity (mV/°)	0.30	0.23	0.16	0.40	0.26	0.13
Angle range (°)	0-4	0-4	0-4	2-5	2-5	0-3
Linearity (%)	97	99	97	99	98	96
Resolution (°)	0.16	0.20	0.28	0.12	0.18	0.36
Resolution (mrad)	2.7	3.4	4.9	2.1	3.1	6.3

4. Conclusion

The operation of two optical-fiber sensors based on angled-mirror reflective modulation is demonstrated. The effects of axial displacement on the detected voltage are measured for three different distances. The highest sensitivity and resolution for the sensor using flat and concave mirror are 0.114mV/° and 7.1 mrad; and 0.40 mV/° and 2.1 mrad, respectively. The sensitivity is affected by the distance between the end surface of the probe and the reflective modulator. Experimental results show that this sensor has capability in non contact measurements, high sensitivity, linear range with low cost of fabrication which make it feasible for many industrial based applications involving direction and micro-angle control in the hazardous environment requirement.

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