Fiber optic displacement sensor for thickness measurement based on transmission and reflection of transparent plate

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A comparison in measuring thickness of transparent plate between transmission and reflection based fiber optic displacement sensor is reported. A series of standard glass slide each with thickness of 150 µm is utilized as specimens. The performance both of the sensor is characterized based on the estimation of the peak voltage, sensing displacement, and slope's variation. The thickness sensor based beam through technique is found to be more pronounces in all aspects compared to reflection one. It is realized to be three times better in sensitivity. Even more prominently in slope variation whereby 65 times compare to front slope and 657 times to back slope. Inherently the transmission based also shown higher resolution. Hence transmission based FODS is more precision system for measuring the thickness of transparent plate in comparison to reflection. Directionality, lack of beam losses during insertion, no scattering, diffusions and absorption involve attribute to such high accuracy of beam through thickness sensor. Furthermore it is more reliable and user friendly sensor since its simplicity in setting, low cost and nondestructive testing and yet enables to provide precision measurement.

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1. Introduction

Over the last decades, measurement of thickness has become increasingly important in numerous fields corresponding to the development of micro to nano-scale technology. In such application, it is essential to have non-contact methods yet highly accurate and precise sensing and measurement system. The optical fiber based sensor fits completely into the need of such applications. It is considered as an attractive alternative over those conventional sensor system such as mechanical and electricity based sensor due to inherent advantages; optical fiber are lightweight and compact, sensitive, low susceptibility to electromagnetic interference, simplicity, and non-contact measurement[1-3]. No electricity is needed at the sensing point due to the optical based; therefore it is a versatile sensor system that allows operating in crucial condition such as chemically hostile or explosive environments [4].

Most thickness measurement optical methods typically revolve around interferometry technique which is sensitive on the optical path difference [5-9]. In more advanced method such as low coherence interferometry and wavelength-scanning interferometry with confocal microscopy [10-13] that deployed refractive index to determine the thickness measurement. Despite offering high accuracy in measurement, these methods required critical and delicate optical alignment thus involved complex setups, bulky system and high cost. Thickness measurement of transparent plate is also reported by using a lateral-shear wavelength-scanning interferometry [14] and unexpanded laser beam [15]. However, in reality the technique is impractical and lack in accuracy.

Basically transparent plates are made of organic and inorganic materials. The plates are widely used in various applications including as liquid crystal display (LCD), transparent semiconductor, protective films, and in optical window applications. Thickness is crucial physical parameter in manufacturing process of the transparent plates [16]. Large scale manufacturing technology of transparent plate desires a high accuracy, simple, robust and cheap technique for thickness measurement which can be offered by fiber optics displacement sensor (FODS). FODS based on reflection technique have been reported [16-18]. However very rare thickness measurement based on transmission of FODShas been published. In this present paper the concept of transmission based FODS will be described in detailed. The performance of transmission based FODS will be demonstrated and compared with reflection technique. Bothtechniques are non-contact and simple but they have significant differences in the way to receive the capturing light that will be discussed in detail later in the text.

2. Principle of Reflective FODS

Reflective FODS has been widely used for measuring thickness of transparent plates [16-18]. The sensor consists of two optical fibers bundled together at one end (one acts as a light transmitting fiber (TF) while the other as a receiving fiber (RF)) and a reflective surface like a transparent plate for thickness measurement. The working principle of the sensor is as follows. A large portion of the light emitted by the TF cores will be transmitted through the transparent plate while only small portion of light is reflected at the surface of the plate. Light cone emerge from the TF is coupled into the RF by reflection of small portion of light from the surface of the transparent plate. By varying displacement of the fiber probe from the surface, variation of output signal carried by the RF will be detected.

Initially the output is minimal at zero displacement since the light cone from the TF does not reach the RF cores. By increasing the displacement, volume of reflected light cone increases and enlarged overlapping with RF cores, thus attributed to linear increment with displacement. A maximum output achieved when the whole reflected light cone falls within the RF surface. Beyond the optimum displacement, only a fraction of the reflected light power will be guided into RF cores. In this case almost an inverse square law relationship will be observed between the output and the displacement between the probe and the transparent plate.

The output characteristics of the reflective FODS have been analyzed theoretically [19-22]. In this experiment 16 receiving fibers and a single transmitting fiber as sensing probe have been utilized. The output power P_N of the sensor is normalized and expressed as [23]

$$P_N = R_{TP} \frac{25}{8\xi^2} \exp\left(1 - \frac{25}{\xi^2}\right) \quad (1)$$

where $$\xi = 1 + \frac{2h}{z_a} = 1 + 2h_N \quad (2)$$

h_N is a normalized distance, R_{TP} is the reflectivity of the plate surface, and z_a is the distance between the light cone vertex with the tip of the probe, while h is the displacement from the plate's surface from the probe.

The output behavior exhibited by the sensor for thickness of transparent plate denoted as *t* is due to the changes in the size of reflected light cone from the front and back surfaces of the plates. The size of the light cone reflected from thicker plate is larger due to the large angle of reflection at the back surface of the plate. Conversely larger size of the light cone is revealed to lower power density at the area of the receiving fibers that eventually produce smaller output power as measured by a detector as depicted in Fig. 1(a) and 1(b).

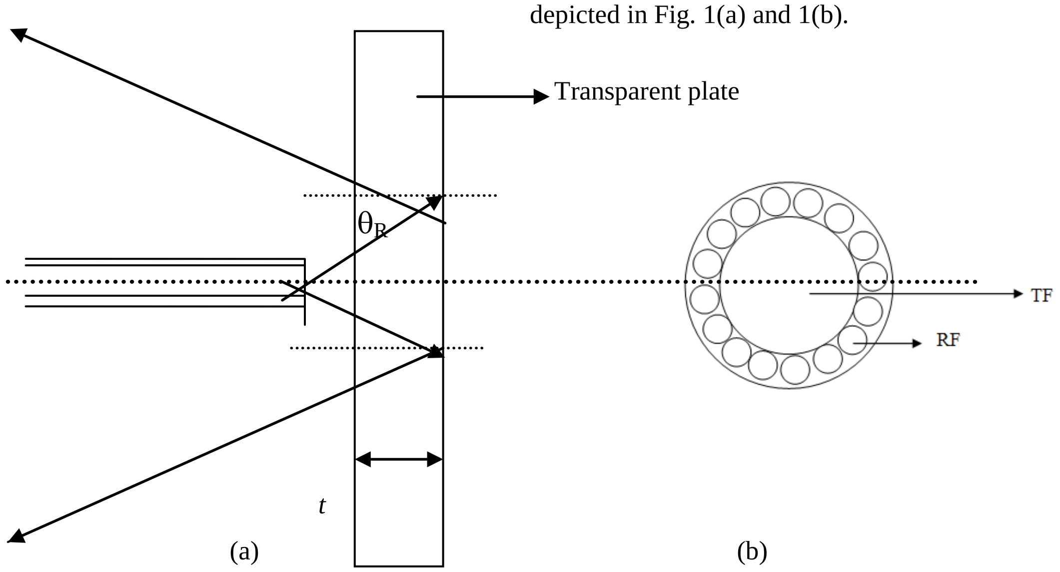

Fig. 1. (a) Reflective fiber optic displacement sensor for thickness measurement; (b) Cross sectional view of fiber optic bundle probe with 1 TR (transmitting fiber) and 16 RFs (receiving fibers).

3. Principle of beam-through based FODS

Light passing through a transparent plate is attenuated by two mechanisms that are absorption of the transparent material and reflection at the interfaces. The first mechanism depends on the path-length of light in the medium, properties of the material, and the wavelength of light. The latter occurswhen the light passes the interface between two media. For a single transparent plate, reflection occurs at both the front and back surface of the plate while when the platesare stacked together reflection occurs at every interface between the plates.

By assuming the transparent plate is homogenous, the attenuated outgoing of light intensity after passing through a series of stacking plate is given by:

$$I = I_0(1 - R)^{2k} e^{-\tau x d} \quad (3)$$

Where I_0 is the intensity of transmitted light, τ is the absorption coefficient, *x* is the distance of light propagated in the plate, R is the reflectivity of the plate surface, and *k* is the number of utilized plate each has the same thickness of *d*. In this manner, by increasing the number of plate, higher attenuation is expected thus the intensity of transmitted light will decrease.

In beam-through FODS, the receiving fiber probe is connected to a photodetector that responsible to capture the transmitted light from the plate. By increasing the displacement between the probe and the transmitting fiber probe, the output transmission should follow the theoretical analysis given by Van Etten and Van Der Plaats [24]:

$$\eta \approx 1 - \frac{z}{a}\frac{2}{\pi(NA)^2}\left[\arcsin(NA) - NA\sqrt{1-(NA)^2}\right] \quad (4)$$

Where η, z, a, and NA are coupling efficiency, axial displacement, core radius, and numerical aperture, respectively.ain text paragraph.

4. Experimental setup

The experimental setup for both techniques: beam through or transmission based FODS techniques and reflection based FODS are shown in Fig. 2 and 3, respectively. The experimental setup has common configurations which consist of a Helium-Neon (He-Ne) laser (633 nm) as a source of light which coupled together with a fiber optic probe. The fiber then connected to a Si photodetector head (Model 883-SL, Newport) and is preliminary connected to a lock-in amplifier (Model SR-510, Stanford Research Systems). The continuous light source is initially modulated to become pulse mode by using a rotating mechanical chopper with a frequency of 63 Hz. A reference signal is fed into lock-in amplifier to allow sensitive light detection free from ambient light interference.

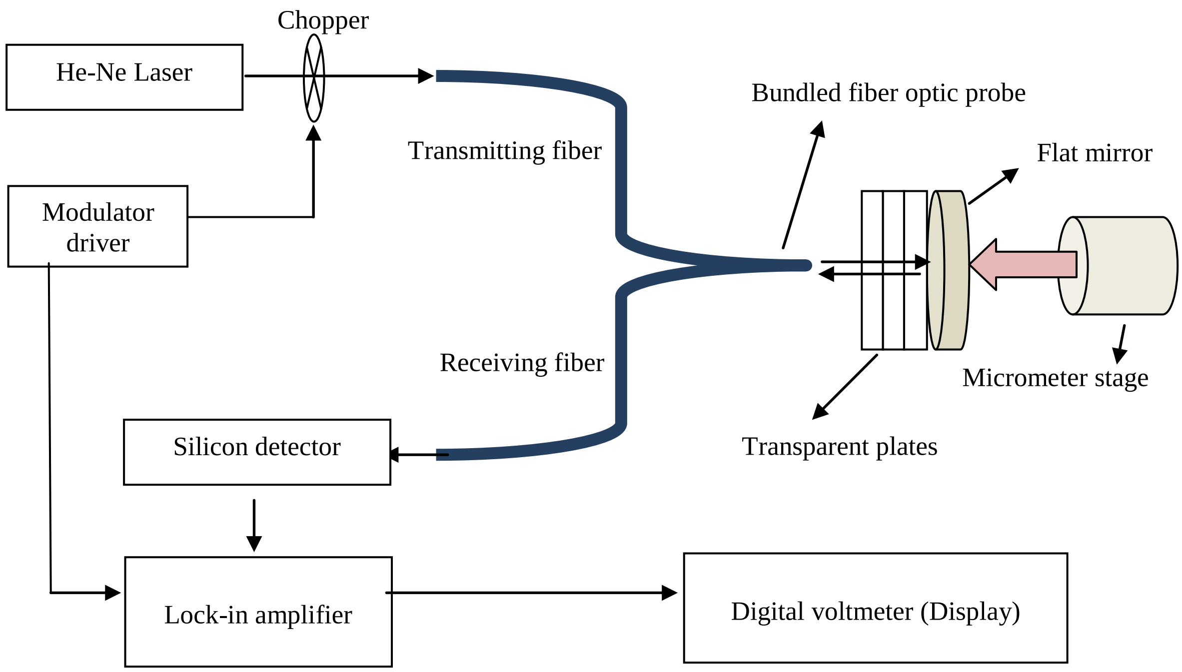

Fig. 2. Experimental setup of thickness measurement using reflection technique.

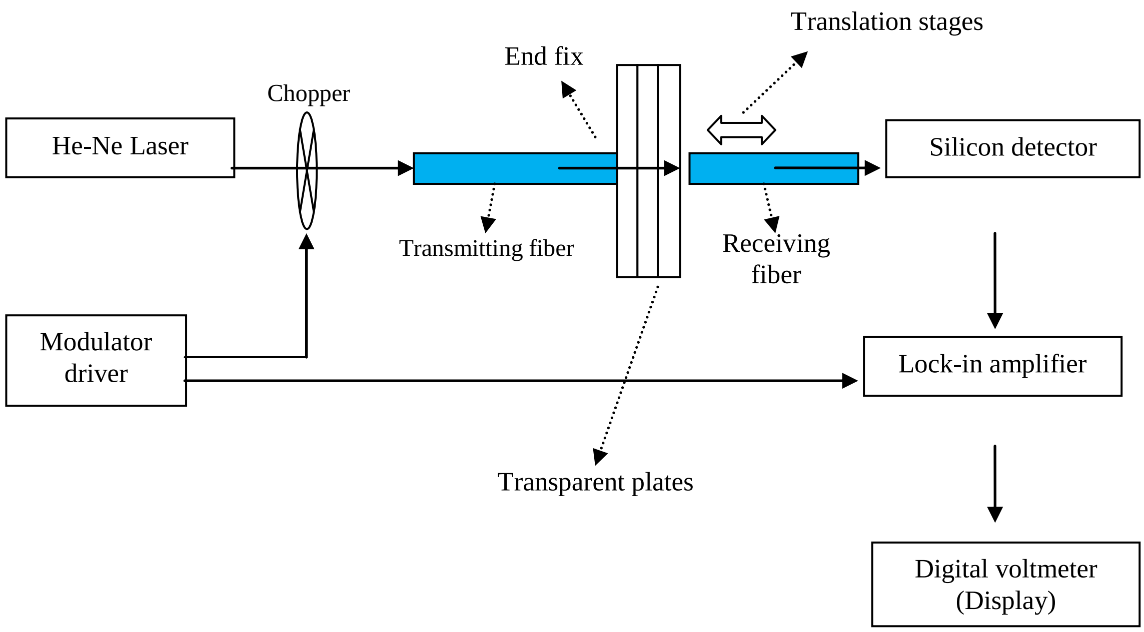

Fig. 3. Experimental setup of thickness measurement using transmitting technique.

In the reflection FODS technique, a bundled fiber probe length is 2 m with 16 receiving fiber cores (*d* = 265 µm) is configured surround a single transmitting fiber (*d* = 1 mm) whereas a single transmission fiber probe (*d* = 1 mm) and receiving fiber probe (*d* = *1mm*) used for beam-through FODS technique. Initially, the experiment for both techniques is performed without the transparent plate (only the plane mirror for reflection FODS). The distance between the mirror (for reflection FODS) and the distance between both probes (for beam-through FODS) is moved away at a step of 50 µm from zero displacement with minimal output. The same procedure is repeated whereby a single transparent plate with thickness of 150 µm is inserted as shown in Fig. 2 and Fig. 3. The same procedure is repeated for the case of 2, 3, 4, 5, and 6 stacked of transparent plates.ain text paragraph.

5. Results and discussions

Initially the stability measurement of the sensor output is performed by measuring the output at a step of 15 seconds for a period of 7.15 minutes such as shown in Fig. 4. It is confirmed that throughout the tested duration, the output signal at different voltages are remained constant. These indicate that the output voltages are stable during the whole duration of experiment.

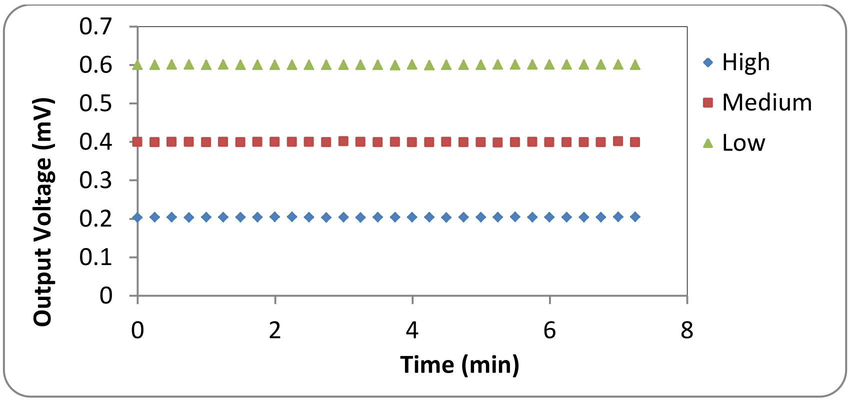

Fig. 4. The stability measurement of the output signal voltage taken for every 15 second for 7.15 minutes.

The output of the transmission FODS technique shown in Figure 5 has decreasing trends with displacement. For the case without the transparent plate, the output at zero displacement is maximal at 0.7 mV. In this particular resultthe light cone from the transmitting fiber enters directly into the receiving fiber. As the transparent plate is inserted, attenuation occurs in which the reflection from each interface is dominant, than other process such as absorption and scattering are involved. By stacking more plates, higher portion of light is reflected as reflection occurs at each interface between the plates. The analysis for linear parameter from the output of the sensor were done at different sensing displacement of 1 mm, 2 mm, 3 mm, and 4 mm as well as the slope’s variation.

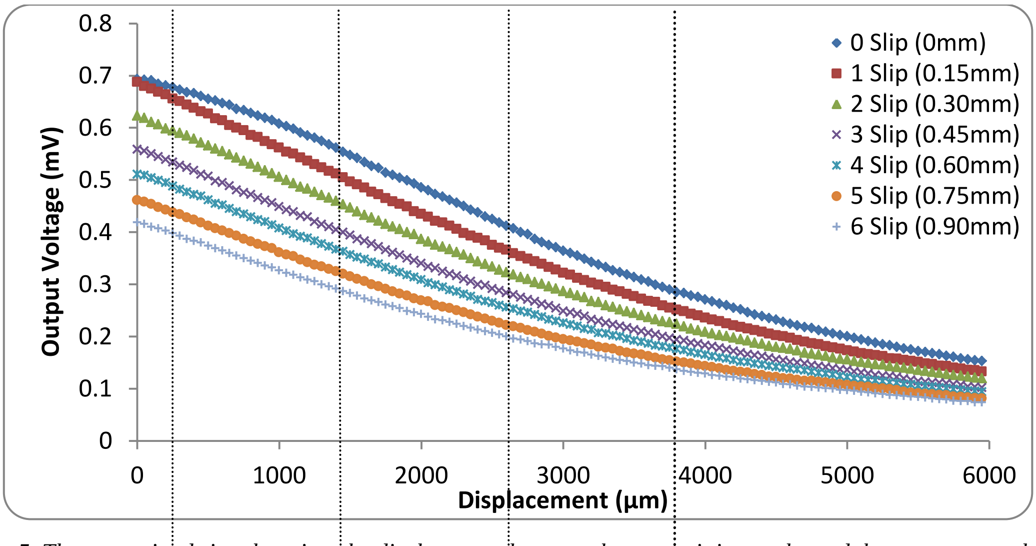

Fig. 5. The transmitted signal against the displacement between the transmitting probe and the transparent plate.

The measurement performed at different displacement of 1, 2, 3, and 4 mm between the transmitting probe and the plates are showed in Figure 6(a). It is realized that all the curves are inversely proportional to the plate thickness.

The slope each of the curve are measured and almost all the curve having correlation more than 99%. The slope variation of each linear region in the output sensor is represented in Figure 6(b). It shows that the transmitted signal linearly proportional to the plate thickness with sensitivity of 4 $\times 10^{-5}$ mV/(µm)^2 with linearity of 99%. Table 1 summarized the sensing performance of beam through FODS based on sensing displacement and slope's variation analysis. It is found that, highest sensitivity is obtained by the analysis at sensing displacement of 1 mm.

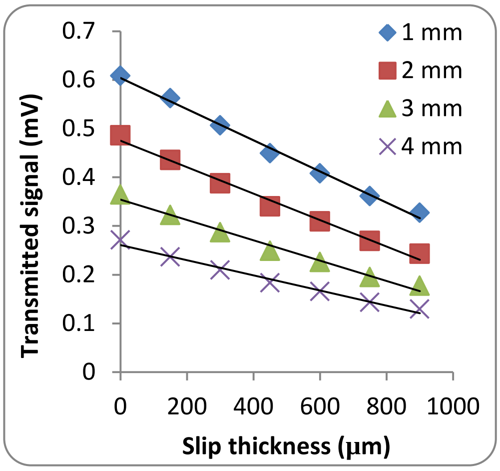

Fig. 6(a). The transmitting signal against the slip thickness at different sensing displacement.

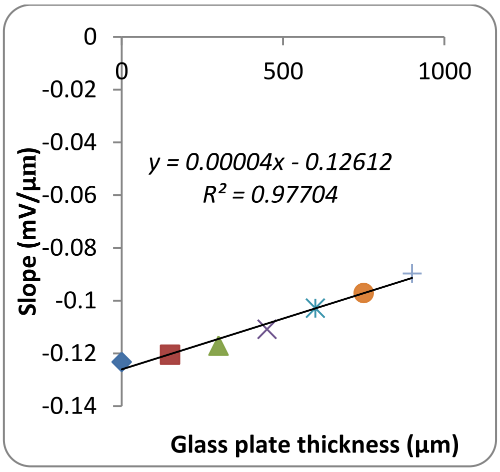

Fig. 6(b). The slope analysis of the fiber optic beam through at different of plate thickness.

Table 1. The characteristics of fiber optic beam through technique.

	Sensing displacement				Slope's variation
	1 mm	2 mm	3 mm	4 mm	
Sensitivity × 10^{-4}	- 3.2 mV/µm	-2.7 mV/µm	-2.1mV/µm	-1.6 mV/µm	0.46 mV/(µm)^2
Linearity (%)	99.7	99.5	99.3	99.1	98.0
Resolution (µm)	18 - 21	21 - 25	28 - 33	38 - 44	-

Fig. 7 presents the reflected output signal measured against the displacement between the bundled probes with the various thickness of transparent plate. It is found that the trends of all curves are almost similar. Each curve drastically increases, achieve peak or optimum output and then gradually decreasing with the displacement. Apparently the maximal signal is achieved when no transparent plate is inserted meaning the total reflected light cone is entirely reveals from the plane mirror toward fiber. However, when the plate is inserted, the light is partially reflected at each interface thus create larger angle of the reflected light cone. The large size of light cone reveals lower power density when entering into receiving fiber, which well agreed with theoretical of Eq. (3).

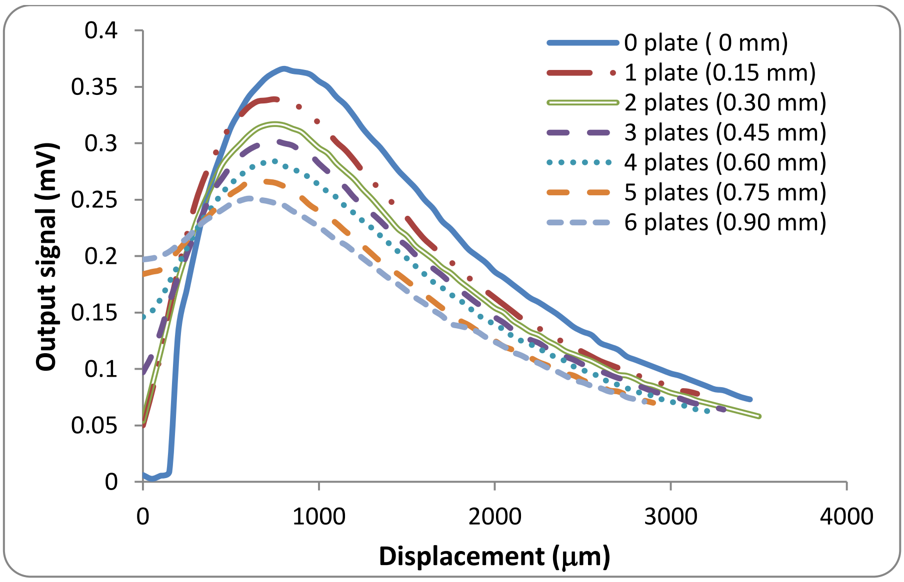

Fig. 7. Output signal as a function of displacement sensor for various transparent plate thicknesses.

Two analyses can be achieved from the output signal of reflection based FODS: peak voltage and both slopes' variation. It is clear from Fig. 7 that the peak voltage is shifted towards shorter displacement for the increasing number of transparent plates. Fig. 8(a) represents the shift of the peak voltage for each thickness of transparent plate. A sensitivity of -1 × 10^{-4} mV/µm is obtained with resolution in the range of 47 to 49 µm.For the second analysis which is based on the slope's variation, the sensitivity for front slope is - 7.1 × 10^{-7} mV/$(\mu m)^2$ while sensitivity of 7 × 10^{-8}mV/$(\mu m)^2$ obtained for back slope with linearity more than 99% as shown in Fig. 8(b). Even though both slopes provide the same linear range of 900 µm, the front slope provides higher sensitivity compared to the back one. The performance of fiber optic thickness sensor based on the both linear slopes is summarized into Table 2. The best performance of reflection based FODS is offered by peak voltage analysis of the sensor output due to its higher sensitivity.

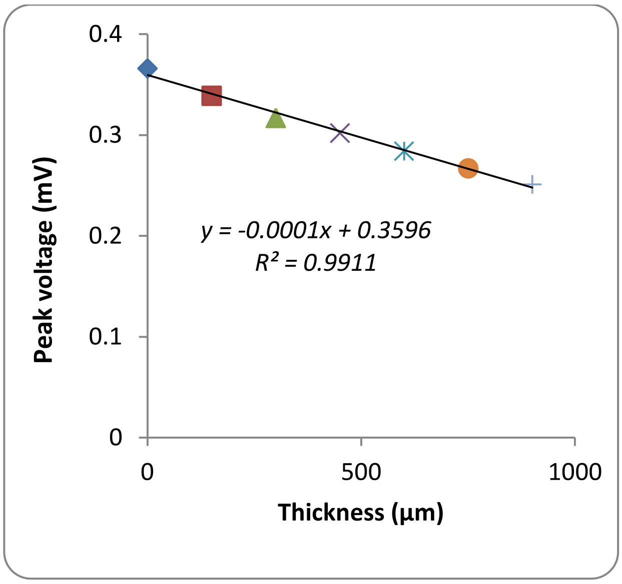

Fig. 8(a): Peak voltage versus thickness of transparent plate.

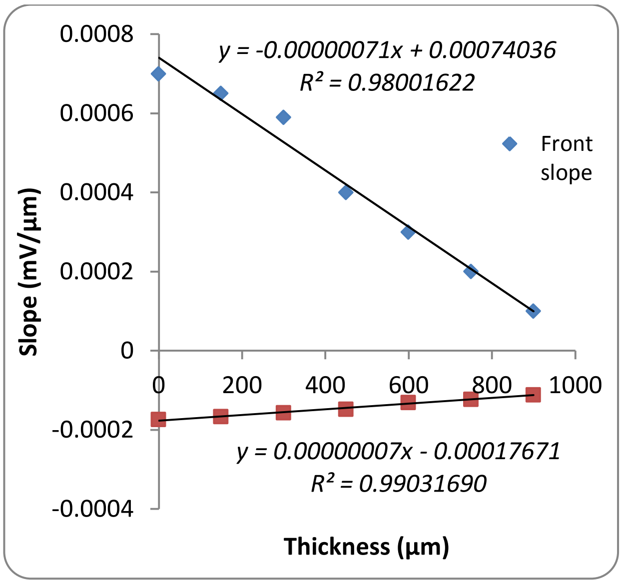

Fig. 8(b). The slope against the thickness of the transparent glass plate.

Table 2. The performance of reflection based FODS technique.

Parameter	Peak Voltage	Front Slope	Back Slope
Sensitivity	-1 × 10^{-4} mV/µm	- 7.1 × 10^{-7}(mV/$(\mu m)^2$)	7 × 10^{-8}(mV/$(\mu m)^2$)
Linear range (µm)	0 – 900	0 – 900	0 – 900
Linearity (%)	> 99	> 99	> 99
Resolution (µm)	47-49	-	-

All linear parameters having correlation of more than 99%, whereas by comparing the sensitivity of the linear parameters of the sensor outputs, highest sensitivity is offered by the beam through technique at displacement of 1 mm between the probe and the plates of -3.2 × 10^{-4}mV/µm. The sensitivity of beam through technique is almost three times higher than the peak voltage analysis from the reflection based FODS. Apparently the slope variation for beam-through of transmission technique is almost 65 times greater than front slope and 657 times greater than back slope of the reflection technique. The thickness measurement from transmission FODS technique at 1 mm sensing displacement provide higher resolution (18 - 21 µm)in comparison to reflection FODS based on peak voltage (47- 49 µm). Hence the transmission FODS technique has shown better performance in measuring thickness of transparent plate based on its greater in sensitivity, slope variation and higher resolution. By correlating the output voltage at 1 mm of sensing displacement, the thickness of unknown sample can be determined between 18 µm up to 900 µm. This technique can be further improved to include measurement of films in smaller thickness region. The demonstration of thickness measurement in this work propose that fiber optic displacement sensor of transmission setups has high potential to provide an accurate non-contract thickness measurement for monitoring and process control, position control, and also measurement in hazardous environment. Further improvement can be made on this sensor design to provide measurement from sub-micron up to nano-scale measurement.

6. Conclusions

In this work measurement of transparent plate has been demonstrate using two techniques base fiber optic displacement sensor (FODS). Apparently the transmission based (FODS) has shown superior performance in comparison to reflection technique.The sensitivity reveals from beam through sensor is realized to be three times greater than reflection technique. The average intensity per unit length (slope) capturing by the transmission sensor is 65 times higher than rise respond and 657 times higher than decay responds of the reflection sensor. Furthermore the thickness measurement attributes from transmission technique is also having higher resolution. Taking advantages of this prominent demonstration any unknown transparent sample then can be implemented by using the correlation betweenthe plate thicknesses with the output voltage at sensing displacement of 1 mm.ain text paragraph.

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