Fiber optic displacement sensor based on micro-thickness measurement using bundled fiber and concave mirror

M. YASIN[a,b], S.W. HARUN[b,c], H. AHMAD[b]
[a]*Department of Physics, Faculty of Science and Technology, Airlangga University, Surabaya 60115, Indonesia.*
[b]*Photonics Research Centre, Department of Physics, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia.*
[c]*Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.*

In this paper, we propose and demonstrate a simple yet accurate optical fiber based sensor capable of performing micron and sub-micron thickness measurement. The proposed sensor is based on reflective displacement sensor, which consists of a 785 nm light source, multimode plastic bundle fiber probe, a concave mirror target and a silicon detector. A mechanical chopper is used in conjunction with lock in amplifier to allow sensitive detection free from ambient light interference. The thickness of the sample can be obtained from a linear equation correlating the thickness of the sample to the displacement of the sensor at which the peak output voltage is obtained, or by correlating the thickness of the sample directly to the peak output voltage measured. The sensitivity of the sensor is obtained at 1.0188mV/mm in the range of 0-0.64 mm of cover slips thickness.

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1. Introduction

Over the last few decades, measurement of thickness has become increasingly important in numerous research and development fields. For instance, measurement of the thickness of transparent plate, which typically ranges from several hundred microns to millimeters. This plate is used in applications such as liquid crystal display and optical windows. Many methods can be adopted for measuring the thickness parameter, whereas optical techniques are the most preferred as they are non-contact and more sensitive. Optical methods are typically based on interferometry techniques, which are sensitive to optical path difference. More advanced methods such as low coherence interferometry and wavelength-scanning interferometry with confocal microscopy [1-3] are normally used to determine the refractive index of the sample, which is then used to provide a highly accurate measurement of the thickness of the sample. The main drawbacks of these methods are they require critical optical alignment and high resolution translation stages [4].

Recently, fiber optic displacement sensors have gained a tremendous interest for various applications [5-8]. In this paper, a simple yet accurate non-contact thickness measurement system using a simple reflective fiber optic displacement sensor is proposed and demonstrated.

The proposed sensor utilizes a multimode plastic bundle fiber as a probe and a concave mirror as a target to perform accurate measurements in the micron and sub-micron range for thick film measurement.

2. Experimental setup

The experimental setup of the proposed micro-thickness measurement based on the reflective fiber optic displacement sensor is given in Fig. 1. The setup consists of a laser diode operating at 785 nm as a signal source and a 2 meter long bundled fiber, which consists of 16 multimode plastic fibre strands surrounding a central core. The central core of the probe acts as the transmitting fibre, which is connected to the signal source, while 16 cores surrounding the transmitting core acts as a receiving fiber, which is connected to a silicon photodiode (818 SL from Newport). The core size of the transmitting and the receiving fibres are approximately 1 mm and 0.25 mm, respectively in diameter. The laser output is modulated at a frequency of 113 Hz using a rotating mechanical chopper. This is to allow light detection using a lock-in amplifier (Model SR-510, Stanford Research Systems) that is connected to the silicon photodiode as to allow sensitive detection free from ambient light interference. The frequency is chosen so as to avoid the harmonics of the line frequency, which is approximately 50 to 60 Hz.

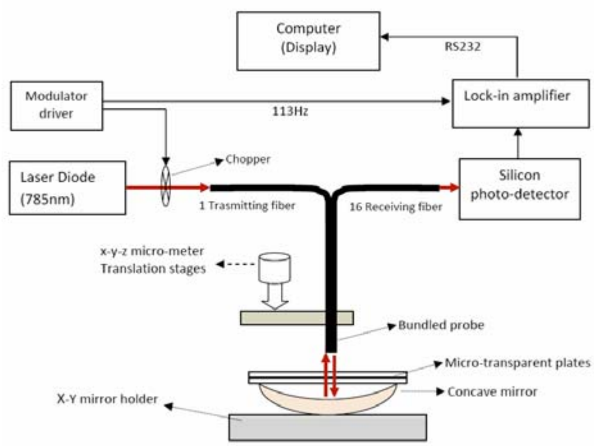

Fig. 1. Experimental setup for thickness measurement using a bundled fiber probe and concave mirror.

The other bundled fiber end, which consists of the central transmitting and the 16 surrounding receiving cores is fixed onto a mount, and is placed on a moveable micrometer translation stage. The glass cover slips (which are used as the sample for the thickness measurements) is firmly fixed onto a X-Y mirror holder on top of a concave mirror which acts as a reflector for the laser diode signal. Initially, the experiment is performed without the cover slip, with only the reflecting concave mirror whereby the fiber end probe is brought as close possible to the surface of the concave mirror without coming into contact. Then, the probe is moved away very slowly in steps of 50 μm for a dynamic range of 15 mm from the concave mirror surface. The reflecting output of the modulated laser diode is measured using the silicon photo-detector that is connected to a lock-in amplifier. The reference signal from the modulator driver is fed into the lock-in amplifier for phase matching with the measured signal. This will allow for a very sensitive detection system that can operate in the presence of ambient light. The output of the lock-in amplifier is then connected to a computer for displaying the detected output voltage. The interfacing is done through an RS232 connection together with Delphi software. This process is then repeated whereby a single cover slip is placed on top of the concave mirror and the fiber probe detects the reflection from the cover slip in a similar manner as in the earlier case. The experiment is also repeated for 2, 3 and 4 cover slips.

3. Results and discussions

The four cover slips are measured with a micro-meter and determined to have thicknesses of approximately 0.16 mm each. The experiment is performed firstly by having no cover slip on the front concave mirror and the output voltage is measured against the displacement of the fibre probe from the face of the sample in steps of 50 μm. The displacement curve is shown in Fig. 2. From this figure, the measured slope sensitivity is approximately 4.93, 1.63, 1.29 and 1.22 mV/mm with a linear range of 600 (50-650), 1750 (1000-2750), 600 (11050-11650) and 300 (11800-12100) μm for region 1, 2, 3 and 4, respectively.

The resolution of the measurement is being determined by fixing a particular position and measuring the output voltage and taking into consideration the voltage fluctuation. The maximum of standard deviation of voltage fluctuation is determined and divided by the sensitivity to result in the resolution of the system that in this case is about 2 μm for the slope of the graph in the region 1. Taking the same approach as in the case of the slope in the region 1, the calculated resolution is about 6, 8 and 8 μm for region 2, 3 and 4, respectively. From this analysis, it can be inferred that the displacement sensor can be used to measure thicknesses in a few tenths of a micro-metre due to its high resolution of 2 to 8 μm for the case of the slope in 4 regions. These results is summarised is given in Table 2. The errors measurement is determined to be less than 0.22%.

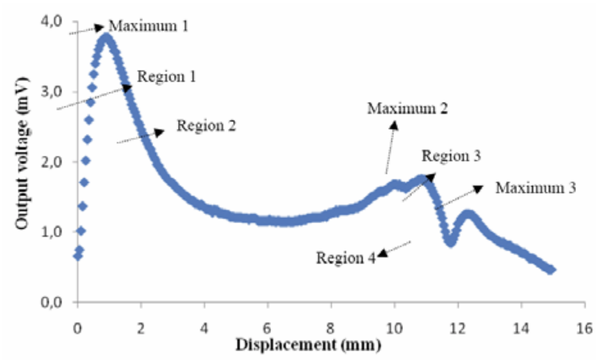

Fig.2 : Output voltage versus displacement of the fiber probe using concave mirror.

Table 1: Characterization of the fiber optic displacement sensor using bundled fiber probe and concave mirror.

Parameter of the sensor	Region 1	Region 2	Region 3	Region 4
Sensitivity (mV/mm)	4.93	1.63	1.29	1.22
A linear range (μm)	600 (50-650)	1750 (1000-2750)	600 (11050-11650)	300 (11800-12100)
Linearity (%)	More than 99%	More than 99%	More than 99%	More than 99%
Error measurement (%)	0.22	0.22	0.22	0.22
Resolution (μm)	2	6	8	8

This experiment is then repeated with 1 cover slip, 2 cover slips, 3 cover slips and finally 4 cover slips and the output voltage against the displacement of the sensor probe is shown in Fig. 3. The curves show that the output voltage profile of the concave mirror shifts for 1-4 cover slips. In these curves, there are three maximum output voltage that can be used to determine the thickness of cover slips. In correlating the data obtained from the sensor to the thickness of the sample, the peak voltage approach is considered. This gives a linear equation on which the thickness of unknown samples can be determined. Fig. 4 shows the peak output voltage against the thickness of the samples. As shown in the figure, the relation is linear with the steepest slope of -1.0188 and a linear correlation coefficient of 0.98.

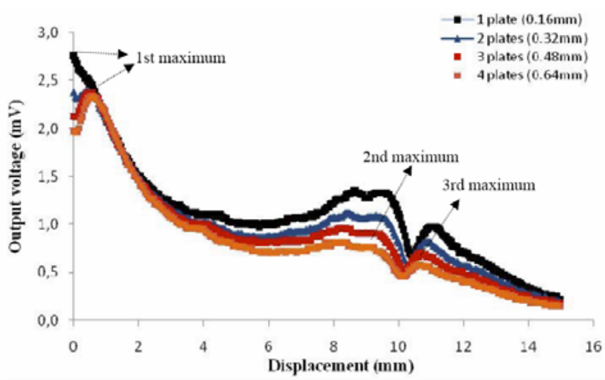

Fig. 3. Profile of the fiber optic displacement sensor for thickness measurement for 1-4 transparent plates.

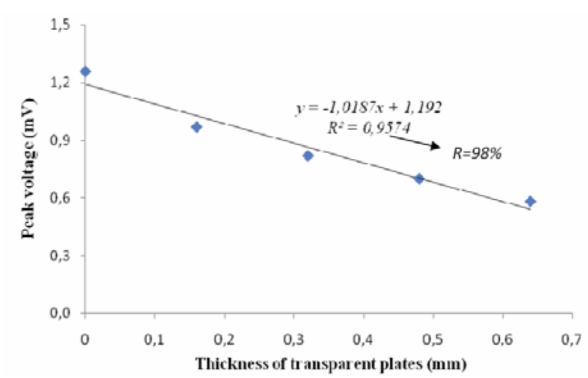

Fig. 4. Peak voltage at the third maximum as function of thickness of the transparent plates.

This method can be further expanded to include measurements of thick films in the region of 10 to 25 μm that are the layers in the fabrication of waveguide devices. Currently, thickness measurements for these thick films are performed using a prism coupler based on the contact technique, and at times can damage the surface of the film. This, in addition to the cost of the prism coupler technique makes the proposed setup a simple and attractive technique.

4. Conclusions

A simple and accurate optical fiber sensor capable of performing micron and sub-micron thickness measurement is proposed and demonstrated. The proposed sensor is based on reflective displacement sensor, which consists of a multimode plastic bundle fiber probe and a concave mirror. The thickness of the sample is computed using a linear equation derived from the correlation of the thickness of the sample directly to the peak output voltage measured at the third maximum. The sensitivity of the sensor is obtained at 1.0188mV/mm in the range of 0-0.64 mm of cover slips thickness. This method can be applied to measure thick films in the region of 10 to 25 μm that are the layers in the fabrication of waveguide devices.

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*Corresponding author: yasin@unair.ac.id, swharun@um.edu.my