Plastic optical fibre power splitter for surface profiling of 3-D object

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Abstract. Single-mode fibre has established the intensity-based surface profiling application with the notable results such as surface topography of ancient stones and three-dimensional rigid-body shapes. However, cost and experimental handling has been the most common issue for single mode fibre related-applications. Thus, plastic optical fibre (POF) has become an alternative for surface structure monitoring due to its highly-multimode and larger cross-sectional area. Millions of light rays can be gathered and enhanced the light detection, aside from lower installation cost and offer easier handling of the fibre system. In this work, the operating principle and experimentation of the surface profiler on a reflective 3-D object is presented. The measurement of the profiler was investigated via a 0.7 dB low excess-loss, non-branching POF Y-shape power splitting coupler. The variation in light intensity reflected from the target surface provides details on the change in depth and thickness of the target. The 1-mm diameter POF end-facet provides excellent probing tip in measuring the diameter of 3-mm reflective spherical surface with good accuracy.

1. Introduction
POF power splitter device has been studied since 1990s, where it focused on plastic optical fibre and cable device. Thus far, POF is still an exploratory fibre due to its low-cost and reliable for short-distance network. However, the advantages among passive devices in the market nowadays not only focuses on performance of the device but also the cost of the product. POF power splitter device is a passive component that found applications in optical communication systems, photonics integrated circuits and optical signal channelling. POF power splitter is very popular among multimode fibre in the development of optical short-distance networks, such as local area network [1], home-network application [2], automation system [3] and optical sensors.

Various types of POF sensor have been reported [4][5][6]. However, due to the large diameter of POF, the intensity distribution corresponds to the modal structure of the POF [7]. The excitation light propagates at varying degrees as it exits the fibre end-facet. Hence, reshaping of fibre tip is realised to rectify the condition, especially for better light guiding and uniform power distribution [8]. POF sensor based on probe tip deformation has been widely used in physical and chemical measurements. It can be used to improve light focusing, light coupling, elimination of Fresnel back reflection, improvise focus distance and adjust light collimation [9].

In this paper, we demonstrate a non-contact optical surface profiler with the ability for thickness measurement of reflective surface object. The 3-dB 1x2 splitter separates the input fibre from the output fibre. The splitter has zero-branching angle at the junction, which is to minimise the bending and propagation loss between the two fibres in the splitter. One end of each 1-m long three connecting POFs
placed at three ports of the splitter converts the circular cross-sectional profile of POF to rectangular via thermal-compressed moulding technique to minimise optical loss in the splitter [10]. As input light incidents on the target via the input fibre and splitter, some of the light will be reflected back towards the fibre tip and propagates to the receiver via splitter and output fibre. The intensity of the reflected light was analysed to determine the surface profile and thickness of the target. The optical system exhibits low optical loss due to the reshaping of the POF cross-section along the mold-insert waveguide slots and by employing the zero-branching angle of the splitter.

2. Experimental Setup
Surface profiling of an object was performed using a home-made 3-dB 1x2 optical power-splitting coupler, where the shape of circular cross-section profile of the POF was molded into rectangular cross-section along the mold-insert waveguide splitter device. The conversion from circular to rectangular profile of the POF fibre is to reduce the propagation and coupling loss between POF and waveguide power-splitter. The experimental configuration of surface profiling is shown in Figure 1. It consists of a He-Ne laser as the light source, a 3-dB POF power-splitter, a reflective target, an XYZ translational stage, a universal motion controller (UMC), a photodetector, a digital multimeter (DMM), and a computer for data acquisition and storage. The 3-dB splitter is to separate the input (laser light) from the output (photodetector) with minimal splitting loss at the junction of the splitter. The 3-dB power-splitter can produce better output resolution for surface profiling as compared to bundle fibres (6). Fibre at port 1, which functioned as a detection probe was set perpendicular to the target surface under study. The other two fibres were connected to the laser light source and photodetector accordingly. The reflectivity measurements were accomplished by placing the reflective target on the XYZ translational stage and moved horizontally under the probe. The micrometer stage movement was controlled by a UMC (model ESP300). The probe was fixed and secured into a position while the target was made to move under the POF probe (from port 1). This is to ensure that any vibration generated from UMC due to the movement does not affect the POF probe and to provide consistency and repeatability of measurement.

![Figure 1. Experimental setup of the intensity-based POF surface profiler system.](image1)

![Figure 2. Principle of surface profiling via reflectivity from reflective surface target.](image2)

The embedded POFs in the Y-junction splitter have similar core cross-section of 0.785 mm². The POF numerical aperture is 0.5, while the refractive index of the core and the claddings are 1.490 and 1.402, respectively. The coherent light source used in the setup is a He-Ne laser operating at 632.8 nm wavelength with laser power of about 3.9 mW. The transmitted power to the surface of target object
under study is about 0.39 mW, measured from an optical power meter. The reduced in optical power was due to coupling loss between POF and the light source, and 3-dB splitting-loss at the junction of the splitter. The position of the light coupling was maintained throughout the experiments by locking the position of the splitter using a customized holder.

The scanning of samples for surface profiling was performed in the x and y direction (length and width), while the z-direction detects the thickness of the target via relative intensity of reflected light from samples. The universal motion controller movement has about 13-mm span, thus the scanning path for all targets was limited to less than 13 cm in length. The POF photodiode (IFD91) detects the intensity of reflected signals. The POF photodiode converts the optical signals to electrical (voltage) signal and was measured using a digital multimeter (DMM - Pro’s Kit MT-1860). Acquisition of data was recorded and saved in a computer via RS232 interface card. The DMM was set to provide high accuracy and resolution of ±(0.5% reading +4 digits) display and 1.0 mV/0.1 mV AC/DC voltage resolution. The speciality of the DMM is that it can acquire continuous data in real time. The performance of the power-splitting coupler was tested as part of profiler component as demonstrated in Figure 2. The He-Ne laser provides light to POF probe from port 2 and transmitted to port 1. Light reflected from the target enters the POF probe and the signal is then transmitted to the receiver from POF in port 3.

The surface profiler was calibrated to ensure accuracy and reliability of measurement. The calibration was done by analysing the reflected signal from the target object within a 3-mm range. Figure 3 shows the calibration configuration where the probe and sphere were near contact. The stage was gradually moved away from the probe to a distance of 3.0 mm. The reflected light outputs to photodiode and DMM, where the measured data was recorded in millivolts.

![Figure 3. Setup for the calibration of the profiler.](image)

Figure 4 shows the variation of output voltage with a displacement of 3-mm of the target object from the probe (POF tip). The amount of reflected light is at the maximum as the POF tip is in the close proximity to the target’s surface. As the probe moves away from the target, the amount of light decreasing polynomially. The slope follows closely to inverse square law relationship and calibration curve will be used as a reference to all measurements. With numerical aperture of 0.5 (30° diffraction angle from POF end-facet), the power density of light reduced due to increase in the size of the cone of light where it spreads to much larger area from POF end-facet as it hits the target. The light diffused away and only small amount of light couple back into the probe. From the calibration curve, the voltage recorded 42.7 mV for the distant of 3.00 mm between POF probe tip and target.
3. Results and Discussion
A 3-dimensional surface profile of a sphere was obtained by moving the target’s stage consecutively along x- and y-directions. The initial scanning of the sphere profile was along the x-direction and gradually moved along the y-direction to cover the whole target’s surface as shown in Figure 5. The probe was set at \( z = 3.0 \) mm from the stage’s surface.

From Figure 6, at \( x = 0 \) mm and \( x = 3 \) mm, the light intensity recorded the background value of about 41.9 mV, where the light was reflected back from surface of the stage that support the sphere and none of the light incident the sphere. The reflected light intensity has a maximum value at \( x = 1.5 \) mm where the probe and the target are close to contact. The signal decreases by scanning x-values in both directions and reaches to a signal near to the background signal. The reason for such decreases is due to the distance...
from the sphere’s surface to the probe has increased and the spherical curvature changed along the movement, which result a lower reflected signal. The measurement on the profile of the sphere demonstrates the significance of the thickness of the target. Thus, using this method we can determine the diameter of the sphere, where the voltage at 3.0 mm distance from the probe showed almost similar values of 41.9 mV from Figure 6 as compared to 42.7 mV from the calibration curve. The main factor that can affect the thickness measurement is related to the contact distance of the target to the probe, whose imperfections and alignment errors can reduce the sensing accuracy.

![Graph showing voltage vs. distance](image)

**Figure 6.** Surface profile of x-scan of the sphere target.

Figure 7 (a) and (b) show the 2D and 3D views of the sphere surface profile. The sphere profile was formed by the deviations of the reflected light. The intensity of the reflected light from the sphere surface depends upon the target’s surface shape and standoff distance between the surface and fibre tip. The signal shows a maximum at scan length of 1.75 mm and reaches to a signal near to the background signal at the target’s sides. However, the surface profile diameter obtained was 3-mm with accuracy of ±1.74%. The reason is because at some point, POF is no longer able to receive any signal due to the too far distance between the target and the probe. Some of the light rays are scattered out of the probe, and some that is able to reach the target is deflected out and did not return back to the probe as shown in Figure 8.
Figure 7. (a) 2-Dimensional view of a 3-mm diameter sphere.

Figure 7. (b) 3-Dimensional view shows intensities obtained corresponding to target’s shape with scan length scale of 19:0.5 mm.
Figure 8. The measured diameter was less by about 33% from the actual diameter of the sphere due to deflection of light out from the sides of the sphere and not reflecting back to POF.

The stability of the device was investigated using similar configuration as in Figure 9. A reflective steel block was used as the target. Marker ♦ denotes the reflected signal of the laser reflected of the steel block over 10 minutes. The average reflectance of the steel block was measured about 437.90 mV with standard deviation of 0.51 mV. For a better comparison, the reflection in photodetector output with no laser light source also shown with marker ■. The average background signal was 3.84 mV with standard deviation of 0.13 mV.

Figure 9. Stability of scanning device when the laser turned on and off as a function of time. The output and the background denote when the laser turned on and off, respectively.

In verifying the x-y plane to be of uniform state, a steel block was placed on the translational stage. The laser emits light to the target block, while the stage moved in x- and y-directions with velocity
of 0.2 mm/s. In order to verify the stage is on the horizontal position, the output signal for every point scanned across $x$ and $y$ must be similar. Hence, uniform beam distribution and precision of surface profiling can be achieved. Figure 10 presents the reflected signal as a function of $x$- and $y$-scan distance. For each scan, the stage movement was set to 10 mm. The plot shows the signal slightly deviated along the distance. Average output signals for $x$- and $y$- directions were 443 mV and 445 mV with standard deviation of 0.6 mV and 0.4 mV, respectively. The deviated signals could be as a result of surface non-uniformity which introduce the light fluctuation and affect the reflection characteristics of the target’s surface. The small output signal differences demonstrate that the surface profiling setup is right and proper for surface profiling measurement.

![Figure 10. The x-y scan of target’s stage for 10 mm scanning.](image)

4. Conclusion
An optical surface profiler device was developed to scan the surface of a reflective target in a non-contact mode. The device relies on the intensity of the reflected light from the target object, where it comprised of a polymer optical fibre tip as the probe attached to a 3-dB 1x2 optical coupler and a coherent light source from a laser. The He-Ne laser can be replaced with a semiconductor laser diode for a more compact and robust device setup. The diameter of the target sphere was found to be 3.0 mm with ±1.74% accuracy, based on the voltage measured from calibration curve (42.7 mV) and scanned profile of the sphere (41.9 mV). The POF-based optical profiler can be used to measure the width, depth and roughness of reflective surfaces. Even though the device could detect width changes throughout the scanning without desired surface profiling, this method could still be exploited for related applications. It would be a valuable device in the future with some development for improvement, as the intensity-based device offers simplicity, portability and compact in size, besides faster scanning time as compared to single mode fibre over the same scanning area, since light emitted from POF has larger spot size.

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