Effect of the Surface Roughness on Cross Sectional Properties of 1×3 Polymer Optical Fiber-based Splitter

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Abstract. This research focuses on the fabrication of 1×3 low-cost splitter based on polymer optical fiber (POF) and the characterization of the surface roughness on cross-sectional properties of the device. Due to the unique features and advantages of POF such as flexibility, low-cost material, and easy to install, POF is also resistant to high temperature and immune to electromagnetic noise (EMI). Thus, fabrication method to produce a 1×3 POF splitter using a low-cost fusion technique has been studied. A fabricated prototype will go through a characterization process by observing the performance of POF varied by the surface roughness of the devices. Two main parameters, such as excess loss and power efficiency percentage are obtained to observe the surface roughness on the fabricated device. The experimental results reveal that surface roughness is not giving a significant impact on the efficiency of the device. However, when it linked to a twisting ratio parameter, surface roughness shows predictable curves on the power efficiency of the low-cost POF splitter.

1. Introduction

In recent years, Polymer Optical Fiber (POF) has become particularly appealing in automotive industry and home networking applications, as POFs are unique. POF is ideal for long-distance data communication up to 20km, wider broadband, high-speed data transfer and has additional losses below 25dB/km once its bent[1]-[4]. Using very inexpensive polymer connectors, POF does not have a significant effect on coupling losses[1] and eliminates modal noise for shorter distances in multimode transmission[5].

POF is an optical polymer fiber with a Polymethyl methacrylate (PMMA) core film inside, which is made of perfluorogenic plastics. The core consists of 96% of its cross-section large fiber to allow light to pass through[6]. POF has a core diameter of roughly 1mm and a numerical aperture (NA) 0.5 in practise. Due to the large core diameter, POF can be easily handled by[5],[7],[8].

Copper wire for communication is slowly being replaced by POF, especially for short range communication in cars and home networking. This is because, unlike POF, copper is not resistant to electromagnetic noise (EMI) and relies on the transmitting distance where the higher chances of failure on data transmission persist[9].

Moreover, POF’s cost effectiveness makes them more desirable and gradually replaces copper wire nowadays. This also happens to glass fiber, its narrowed core diameter makes them very brittle and
difficult to handle. This adds to the higher installation cost since only a specialist with advanced expertise will install it. Although glass fiber has low attenuation and higher bandwidth than POF, the cost limitation has resulted in people preferring POF over glass fiber for short distance communication[10].

In this study, a low-cost 'green-tech' fusion technique is implemented to produce a 1×3 splitter. This technique uses no dangerous chemical or complex system which requiring extra rate. Instead, it uses easy-to-find and regular equipment that significantly reduced the cost of production of 1×3 splitter, that already present in today's world market. Seeing the quality of the handmade 1×3 POF splitter, this device undergoes multiple characterization processes. Numerous digital data will be simultaneously transmitted to the network using these splitters to measure the quality of the fabricated POF splitters.

The low-cost POF splitter contains three pairs of pigtail ends positioned one beside the other and having a straight biconically tapered coupling area interposed between them. The optical splitter described herein is made of multimode optical fibres. These splitters involved, in particular, the heating arrangements for the intimately contacted optical fiber segments to fuse the segments together. The invention has a general application to multimode fibers and couplings. With the increase in throughput needed for today's networking infrastructure, there is a need for greater speed, larger bandwidth, lower cost, optical fiber devices due to the advantages of fiber optics over various other media. The benefit of fused fiber couplings has become increasingly obvious due to these needs. The present invention refers to the apparatus and the surface roughness effect of the splitter and see how far this parameter can affect the power efficiency of the splitters.

The surface inspection of the cross-section of the three fused optical fibres includes surface roughness, Ra and microstructure analysis. All three optical fibers were injected with LED light having the same wavelength as that of red light with a wavelength of 650nm. At the same time, the cross-section of the LED luminous tapered region of the three fibers was observed under a microscope. Afterwards, Ra value for the cross-section of the three fused fiber is observed and measured using ImageJ computer tools.

2. Material and Methods

The goal of this analysis is to fabricate and characterise the 1×3 POF Splitter. Next, the prototype devices must be fabricated and advanced test characterization conducted. To compare the output with the measurement results a set of optical splitter samples have been produced. The fusion method is used to produce this process.

The characterization method is carried out on the basis of both samples' tests and measurements. The objective is to assess the output of the fabricated splitters. The multimode step index POF with 1mm core and 0.5 numerical aperture for production and characterization methods were selected for this analysis.

The fabrication of the optical splitter consists of three POFs which are fused and bundled into three optical splitting components. It must be handled gently to avoid any damage to the bodily structure of the POF. The optical splitter fabrication process is low cost, as the methods can be used without any special equipment and releases no dangerous gases like nitrogen, sulphur, carbon and so on. The 'green-tech' initiative is also being promoted by its procedure.

In addition, the procedure can be conducted manually by a skillful hand using a steel tube and Bunsen burner, but this process takes more time and effort in order to achieve the proper fusion technique. This leads to loses. Figure 1 displays the process flow for the fabrication of 1×3 POF Splitter.

Figure 1. A process flow diagram of 1×3 low cost POF-based splitter.
2.1. Cutting and remove coating
The POF must be cut and the jacket removed before the splitter is fabricated. Cut the POF into three pieces with the same cutter length about 200mm. The cut must be placed at the correct angle. This assures that the end of the POF is uniform and that rough surfaces are minimized. Then the jacket must be stripped and only the core and cladding must remain.

2.2. Twisting and pulling
This method uses three POF fibers that had to be twisted, pulled and protected with a metal sleeve. The POF must be twisted so that the light will travel into the splitter and reflect precisely. All three (bundled) POFs will be simultaneously bent and fused. The heating will then be carried out over the POF. The heating cannot be applied directly to POF and the metal sleeve is also expected to cover POF to minimise the damage to the physical layer of POFs. Pulling and twisting during the fusion process must be performed consistently and smoothly. Heating should be carried out not more than 12 to 15 seconds to prevent damage to the body structure of POFs.

2.3. Fabrication of the splitter
The fusion process will take place after the heating process. The fusion process means that all three POFs have been combined to stretch and narrow the fiber until it center part becomes one single POF with a diameter of 1mm. This is the same as the previous heating and twisting process. The procedure is continually carried out until the center part of the bundled POF is fused and lengthened. The POF may then be removed from the metal sleeve.

After the successfully developed POF optical splitter, the POF must be characterised in order to identify the efficiency of the splitter. As much as 76 samples of 1×3 fused tapered POF splitters have been labelled with numbers 1 to 76. Each splitter must be able to pair the incoming light into a single output signal with less power loss.

The power loss indicates the drop in optical signal power along the splitter. The fusion character and the efficiency of the optical splitter would be the key factor in deciding the power loss in each optical splitter output signal. The low power loss means the system works well. The characterization must then be carried out to validate the performance. All experimental data were collected, checked and analysed particularly for signal output and optical power loss.

2.4. Characterization process
The procedure continues with the POF splitter being polished. Micro-scale sand paper will polish the end portion of the POF-based splitter. The end-ports of the POF can be polished vertically so that the surface of the POF is even and it has to be polished gently in a circular direction. Together with the LED power source, the power meter was used entirely to calculate the output power and optical power loss. Power meter is measure in \(\mu\text{Watt}\) and dBm. 3×3 POF-based splitter now comprises of the left and right regions, which have three ports of input and output. LED of 650 nm wavelength will be emitted at one of the POF fiber at the left side for initial measurement.

The power meter for all three fibres on the right side is used to calculate the output power. The obtained values will be recorded. For the other POF sections on the left part, this procedure needs to be replicated and labelled as forwards. After that, the procedure is repeated again by moving the LED on the right and the power meter on the left side and marking is performed as a reverse bias. This process is conducted for all fabricated POF as seen in Figure 2 below to check the efficiency for both regions and decide which the best regions to be utilized as a 1×3 POF-based splitter by remove the regions which less efficient in term of transmitting the optical power.

![Diagram of LED and POF pieces](image)

LED with 650nm wavelength emitted to one of the POF piece.

The red light from the LED goes out from the end of the three POF pieces.
Figure 2. The characterization process of the low cost POF-based splitter.

Next step is to observe and quantify the cross-section region of the three fused fibres using computer software called ImageJ. With this programme, the cross-sectional calculation process can be simpler, more effective and quicker without wasting a lot of time. ImageJ software is a random domain-based Java image processing tool designed by the National Institutes of Health.

Ra is the parameter of surface roughness of the cross-section region of the fiber affected by the heat treatment and polishing effect in the tapered region. Monitoring procedures are carried out to verify the effect of the twist and the surface roughness of the smallest diameter of the POF’s center region of the fiber output terminal. The measurement of the POF diameter was done using a digital caliper. A red LED with a wavelength of 650nm is used as a light source on the input terminal. Percentage of efficiency is a measure of the overall output power of the three terminals to the input power.

3. Results

3.1. Structure and cross-sectional properties of splitter end surface

Interface orientation characterization for cross-sectional area of 1×3 POF splitter using ImageJ software can be observed by Figure 3 below.

Figure 3. Images of surface roughness on cross sectional properties of 1×3 POF splitter using ImageJ software with (a) severe, (b) moderate and (c) good surface roughness.

3.2. Variation of power output against surface roughness

Ra is the value for surface roughness of the fiber cross-section affected by the fusion process in the tapered region. Monitoring is undertaken to see the effect of the twist and the diameter of the tapered fiber region. Digital caliper measure the POF diameter. A 650nm red LED is used as a light source at the input terminal. The efficiency percentage shows a contrast between the overall output of the three terminals and the input power. Figure 4 illustrates the correlation between the cross-section surface roughness, excess loss and device performance.

Figure 4. Data observation for surface roughness, Ra (μm) of 76 POF-splitter samples in affecting the device performance represented by (a) output power, Po (μW) and its (b) excess loss, EL (dB).
3.3. 3D-contour analysis on surface roughness

3D-contour observation analysis was also performed using two separate variables which affect system performance. A direct correlation of these two independent variables would be observed, whether it affects the device's performance or not. GetData Graphics Digitization Program identifies all three variables. The contour curve as shown in figure 5 will be analysed along with the rise or drop of all independent variables value, whether it will form a stable contour or not towards the device efficiency.

![Figure 5. 3D-Contour diagram for excess loss due to the variaty of (a) tapered angle vs. length and (b) twisting ratio vs. surface roughness.](image)

4. Discussion

Refer to the cross-sectional characterization of optical splitter via ImageJ, figure 3 shows that the structure of the surface can be categorized into three classes, it is severe, moderate or good surface roughness, $Ra$. The splitter is created by shaping two parts of two multimode fibers of the biconical taper sections, pulling together the fibers and heating up a region in the tapered regions, which can be fused together. Problems include the idea that twisting the fibers also leads to increased excess loss. Consistent tapers from one connection to another are often harder to obtain. And the typical excess loss, $EL$ range for this particular coupler is between 5 to 10dB.

Twisting the fiber together has two main disadvantages: 1) the twist tends to cause a loss of the microbend in the fiber and raises the excess loss, $EL$; 2) the experience of the researchers has demonstrated that twisting often makes it difficult to control the taper process. The fibers are in contact for a very short period in the twisted area and this may result in the tapers too sharp, in a way that fiber have a higher twisting ratio, $\Delta t$. The damage caused by the polymerization reaction may be serious if the crests are too steep or sharp. The researchers have also shown that if the strain in the twists is not balanced, this twist will travel along the fiber lengths. The resultant taper profile varies whether the twisted area shifts away from the heat source core while the fusion is performed or only off-center. Therefore, it can be a challenging source of unreliable and unreproducible tapers unless the twist is automated and properly performed.

When it come to the parameter of surface roughness, $Ra$ alone, it does not directly affect the efficiency of the optical splitter. Figure 4 does not show a significant graph trend by the increased of each $\mu m$ of surface roughness of the cross-sectional area of the splitter. The curve is almost flat by mean that the sample data are randomly distributed. By the increased of the surface roughness of the fiber-end, the excess loss, $EL$ mostly laid between 5 to 10dB.

Excess loss of the twisted fiber, $EL$ has been calculated due to the variation of the surface roughness of the cross sectional fiber. Figure 4 Shows the variation of the percentage of the power efficiency as well as the $EL$ in a range of $34\mu m< Ra <80\mu m$. The graph also indicates the power efficiency form an
insignificant linear line. Therefore, the relationship between \( Ra \) and the efficiency of the devices can be represented by the following power equation:

\[
\%P = 6.47Ra^{0.39}
\]  

(1)

and its relationship with its \( EL \)

\[
EL(dB) = 291.01Ra^{-1.12}
\]  

(2)

Where \( \%P \) represents the percentage of power output of the device, the percentage obtained increases linearly when \( Ra \) increases because the optical power reaches its optimum value \((EL \approx 3dB)\) continuously when \( Ra \geq 59\mu m \). At \( 59\mu m \leq Ra \leq 80\mu m \), it was found that the highest percentage of output power obtained was in the range between 40\% to 100\%. While at \( 34\mu m \leq Ra \leq 59\mu m \), the average device efficiency is at the level of 10\% to 40\% only. The value of \( Ra \) is quite varied in terms of value and its fiber structure due to extrinsic errors that occur in cross section as well as due to surface structural defects as a result of polishing, heating, fusion and cutting of tapered area.

Compared to one single variable \( Ra \) against power efficiency, 3D contour analysis provides a precise prediction for the power output of the device. Tapered ratio, \( \Delta t \) indicates a ratio of number of fiber’s twisting, \( nt \) over the 1mm tapered length, \( l_t \). While tapered angel, \( \theta_t \) represent the tangent of diameter of the tapered fiber, \( d_t \) over the tapered length, \( l_t \). figure 5(a) shows a more flatten \( EL \) contour plane and leaning to one of the axial angles against both variables \( \theta_t \) and \( l_t \). Excess loss is in the range of -11dB to 41.40dB. This \( EL \) contour texture consists of a descending valley and one highest peak.

The \( EL \) dropping valley composed by combination of two variable range value between \( 1^\circ \leq \theta_t \leq 6^\circ \) and the value of \( 0 \leq l_t \leq 15 mm \). The lowest \( EL \) value reaches -11dB. This is the most optimal value for both \( \theta_t \) and \( l_t \) variables to be selected to ensure that the device has the optimum performance and the least excess loss. The \( \theta_t \) approximation value of the optimum condition is between \( \theta_t \leq 3^\circ \) area and the value \( l_t \) is \( l_t \leq 7 mm \).

The contour plane has one main peak marked with the dark red color with the maximum excess loss in between \( 6^\circ \leq \theta_t \leq 17^\circ \) and \( 20mm \leq l_t \leq 50mm \). This highest peak has an excess loss reaching 41.4dB. The \( EL \) contour plane is slightly upward and down (not noticeable) and appears to be inclined towards both \( \Delta t \) and \( Ra \) to one of the axial angles (refer to figure 5(b)). In the range of -11dB to 21.60dB, excess loss is achieved. This \( EL \) contour structure is constructed by a dropping valley and several minor hills, but there is only one major peak. The drop valley laid between two variables \( 1^\circ \leq \theta_t \leq 6^\circ \) and \( 0 \leq l_t \leq 15 mm \) value where the lowest \( EL \) reached -11dB. This is the best value for both variables \( \Delta t \) and \( Ra \) to be chosen to ensure the excess loss throughout the device to be minimized. The contour surface has one highest point in a dark red hue, with a maximum loss laid between \( 6^\circ \leq \theta_t \leq 17^\circ \) and \( 20mm \leq l_t \leq 50mm \). The highest peak has an excess loss of 21.6 dB.
5. Conclusions
As there is no use of dangerous chemical compounds, the process is used in the application of the fusion technique to produce ecologically friendly 1×3 POF splitters. In addition, this provides lower fusion technology costs in the production of 1×3 POF splitters that can later be added to a range of short-haul applications such as home networking, In-Vehicle Infotainment (IVI) systems, and so on.

This fabrication method is used to produce 1×3 POF splitters, which process is more practical and very convenient as it only uses a candle to release heat for the POF fusion and a piece of metal tubing to protect the POF from directly exposed to the candle flame heat. There are disadvantages, however, including as the 1×3 POF splitters cause higher losses. This is attributed to limitations on hands-on application.

Surface roughness alone does not have a significant influence on the performance of the splitters. Nevertheless, since we add tapered ratio parameter, both variables will have a precise assumption on splitter’s excess loss. If we want to increase the efficiency of the splitters in the future, we may be able to use these two parameters to refine the calculation.

Acknowledgments
This work was financially supported by the research grant under Ministry of Higher Education Malaysia numbered KK-2019-017, AP-2014-002, GUP-2019-010 and DIP-2018-017.

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