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# Analysis of biconical taper geometries to the transmission losses in optical microfibers

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Optical microfibers have been fabricated using a fusion splicer by varying a few control parameters, namely the arc power, fusion time and pulling distance. The geometrical characteristics of the optical microfibers such as length of the transition region and waist, taper angles and cladding diameters are believed to play a role in determining the optical transmission losses. This study revealed the advantage of the one-sided pulling technique to produce small diameter of cladding and core of the optical microfiber namely, 1.43 µm and 0.67 µm respectively with the waist length of 7.35 µm. Strong oscillations of light propagation were observed when the cladding diameter was less than 2µm. The optimum ratio of the taper angle and the transition length are 0.75 and 1.27, respectively with a transmission loss percentage of 16.03%.

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*Keywords:* Optical microfiber, Taper angle, Transmission losses, Transition length, Waist length

## 1. Introduction

Today, fiber optics sensors have found increasing applications in various fields due to their low losses and compactness compared to lithographic photonic circuits [1-3]. Fiber optics sensors can be fabricated by tapering the single mode optical fibers to form microfibers. Tapering is a technique where a section of the optical fiber is heated to its softening temperature [4]. Then, the optical fiber is pulled slowly to attain the desired radial profile in the tapered section. Tapering can be done using a heat and pull technique by employing two types of heating sources, namely flame brushing or electric arc discharge. Wet chemical etching technique is another option for the fabrication of the optical microfiber [5]. Nevertheless, this technique is very harmful due to the employment of a hazardous chemical, namely hydrofluoric acid.

In this experiment, an electric arc discharge which acted as a heating source is used to melt the optical fiber. The heating and pulling processes are conducted simultaneously to form the optical microfiber from the standard optical fiber. When the fiber is tapered, the waist region would have a diameter in the order of a few microns and the core would almost vanish. The taper transitions transform the local fundamental mode from core mode in the untapered fiber to cladding mode in the taper waist [6].

Fig. 1 illustrates the shape of the optical microfiber. Geometrical properties of the biconical taper such as the radius of taper waist, the length of taper waist and the length of taper transition affect the light propagation and the structure's losses [7,8]. Few works have been conducted to investigate the effects of the geometrical properties and the optical properties of the optical microfibers to the behavior of light propagation [9-15].

To the best of the authors' knowledge, this is the first time a detailed analysis of the optical microfibers fabricated using the fusion splicer technique is discussed. We report the behavior of light propagation inside the microfiber during the tapering process. The effect of taper geometries to the transmission losses was also investigated. Else than using a cost-effective heat and pull technique, a new equation that relates the taper angle ratio, $\theta_{ratio}$ to the transmission loss was developed.

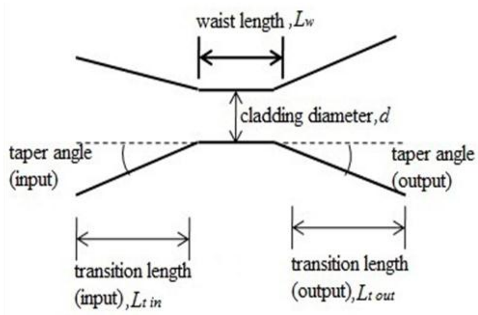



*Fig. 1. Illustration of the optical microfiber.*

## 2. Methodology

Optical microfibers were fabricated using an automatic fusion splicer type-36 (Sumitomo) by heating the single mode optical fiber (SMF-28) using an immobile electric arc discharge under the fiber. The main control parameters are pulling distance, prefusion duration, fusion duration and supplied arc power.

To observe the effect of taper geometries to the transmission power in the optical microfibers, two types of pulling techniques were employed, namely one-sided pulling [16-18] and two-sided pulling. Fig. 2 illustrates the optical microfiber fabricated using the one-sided pulling technique. The optical fiber was clamped on the V-grooves as shown in Fig. 2(a). We conducted the heat-and-pull process by monitoring the control parameters of the fusion splicer. Whilst the pulling process was performed by setting the pulling distance at 56 µm and increased slowly until 340µm, the heating process which is represented by the values of the arc power was set from 15 steps to 132 steps. The fusion and pre-fusion time were set within 21s and 1.34s, respectively. During the heating and pulling processes, we investigated the characteristics of the optical light propagation by observing the transmission losses. In the one-sided pulling technique, only one side of the fiber clamp was moved. Another side of the fiber clamp remains fixed as illustrated in Fig. 2(b). The one-sided pulling technique was used in order to fabricate biconical tapers with different taper angles. As shown in Fig. 2(c); the profile of optical fiber was changed during the pulling process. The optical fiber absorbed the heat produced by electric arc discharge and melted instantaneously [16]. The optical microfiber was formed which is identical to a standard fiber except that the overall diameter of the fiber has been substantially and gradually reduced in one localised region. The optical microfiber was located between these two biconical tapers.

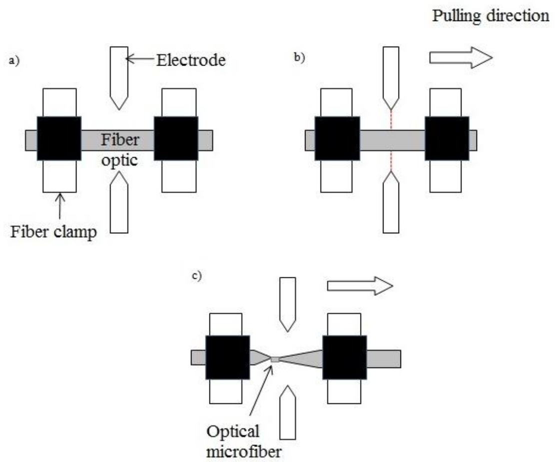



*Fig. 2. Fabrication of the optical microfiber using one-sided pulling technique.*

Conversely, both fiber ends were pulled during the tapering process in the two-sided pulling technique. We set the pulling distance at 56 µm and slowly increased the distance until 180 µm. Simultaneously with the pulling process, the arc power was increased from 15 steps to 106 steps. Value of the fusion and pre-fusion time were set at about 12.8s and 2.02s, respectively. It was clearly observed that the pulling distance for the two-sided pulling technique was shorter than the one-sided pulling technique. In comparison between both techniques, the latter technique caused the microfiber to break easily as compared to the former due to the fact that the forces applied are larger than the one-sided pulling. Nevertheless, careful and gentle handling should be observed during the whole fabrication process owing to the properties of the microfiber which is fragile and sensitive to vibration.

To observe light propagation during the tapering process, one end of the optical fiber was connected to the 1550 nm wavelength of a laser source (EXFO laser source); meanwhile the other end was connected to a power meter (Newport FM-200) as depicted in Fig. 3. Before entering the waist region, the light propagates in the fundamental mode of the single-mode fiber. The light propagates down the taper and is coupled back into the single-mode fiber at the exit end of the tapers.The characteristics of the optical power transmission was studied during the tapering process using an optical power meter. The effects of taper angle ratio (input to output), the transition length ratio (input to output) and the cladding diameters to the transmission losses were investigated.

The taper angle ratio can be determined using Eq. 1 as follows:

$$Taper\quad angle\quad ratio, \theta_{ratio} = \frac{input\quad taper\quad angle}{output\quad taper\quad angle} \tag{1}$$

The transition length ratio, $L_{t\ ratio}$ can be obtained using Eq. 2:

$$Transition\quad length\quad ratio, L_{t\ ratio} = \frac{Input\quad transition\quad length}{Output\quad transition\quad length} \tag{2}$$

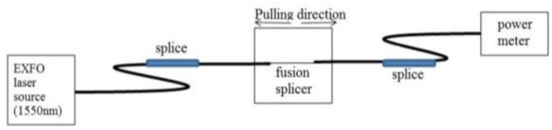
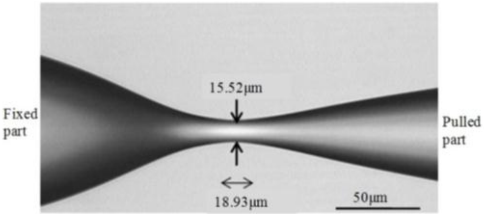



*Fig. 3. Experimental setup to observe light propagation during the tapering process.*

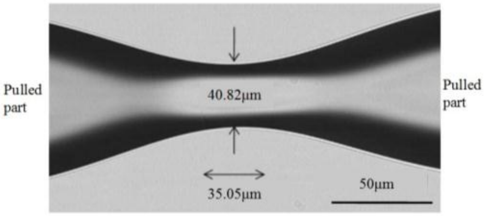
## 3. Results and discussions

### *A. Comparison between one-sided pulling technique and two-sided pulling technique*

In the process of tapering, a section of the fiber is heated to its softening temperature and axially stretched until the desired diameter reduction is achieved. Fig. 4 captures the geometrical properties of the optical microfibers fabricated by the different types of heat and pull techniques. We firstly discuss the geometrical properties of the optical microfibers fabricated by the one-sided pulling technique as illustrated in Fig. 4 (a). The fixed part of the fiber forms a large taper angle; meanwhile the pulled part forms a small taper angle. By applying a pulling velocity of 15.66 $\mu ms^{-1}$ and total arc power of 124 steps on the fusion splicer, the optical microfiber with cladding diameter of 15.52 µm and waist length of 18.93 µm was obtained. Fig. 4(b) depicts the optical microfiber which was fabricated using the two-sided pulling technique. Cladding diameter and waist length obtained were 40.82 µm and 35.05 µm by controlling the main parameters on the fusion splicer. The input and output transition regions formed the same taper angles approximately.




(a) The one-sided pulling technique




(b) The two-sided pulling technique

*Fig. 4. The optical microfiber fabricated using different types of pulling techniques as observed under the optical microscope with magnification of 20X.*

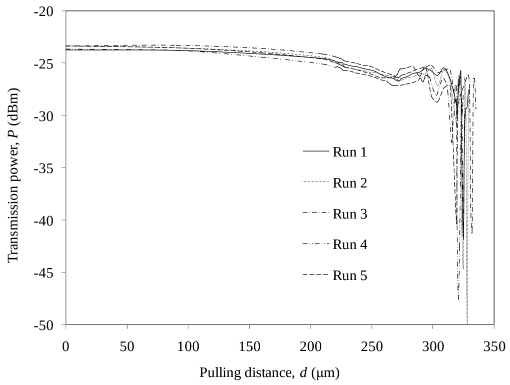
The analytical properties of the optical microfibers fabricated by one-sided pulling technique and two-sided pulling technique are highlighted in Table 1. With the employment of the one-sided pulling technique, the maximum taper angle of 22.91° at the output transition region and the minimum taper angle of 8.96° at the input transition region have been obtained. Evidently, the ratios of the taper angles which are between 0.50 and 0.7, proved that the values of the input taper angles are approximately one-half smaller than the output taper angles. This technique reveals that the one-sided pulling can be used to produce biconical fiber tapers with different taper angles. Meanwhile, the taper angle ratios obtained are within 0.90 to 0.93 using the two-sided pulling technique. Consequently, biconical fiber tapers with similar taper angles geometry between both input and output transition regions can be produced using this technique. It is worth mentioning that larger taper angles at the output transition region are preferable considering the high transmission losses which are experienced by the optical microfibers. Therefore, the one-sided pulling is a favourable technique due to its capability to produce larger output taper angle which leads to small energy losses.

*Table 1. Geometrical properties of the optical microfiber fabricated by different types of pulling techniques.*

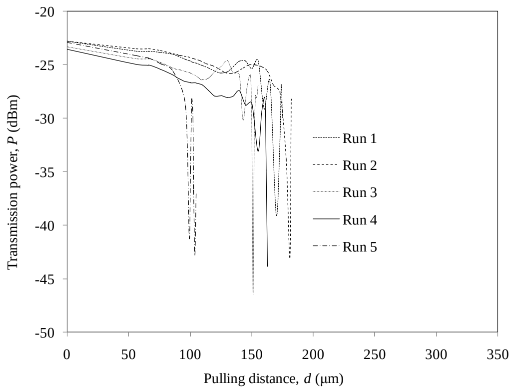
| **Geometrical properties** | **One-sided pulling technique** | **Two-sided pulling technique** |
|---|---|---|
| Minimum input taper angle, $\theta_i$ (°) | 8.96 | 12.59 |
| Maximum output taper angle, $\theta_o$ (°) | 22.91 | 18.36 |
| Range of taper angle ratio (input to output) | 0.50 to 0.74 | 0.90 to 0.93 |

Fig. 5(a) and 5(b) depict the characteristics of the transmission power during the tapering processes using one-sided pulling and two sided pulling techniques, respectively. In comparison between both figures, it is clearly observed that the pulling distances for the one-sided pulling technique are two times longer than the two-sided pulling technique. The former technique resulted in smaller diameter of the optical microfiber than the latter one due to its longer pulling distance. Owing to the pulling forces applied on both ends of the fibers, the optical microfiber fabricated by the two-sided pulling technique is more fragile than the one which was fabricated using the one-sided pulling technique due to the greater pulling force which was applied on the optical fiber. Consequently, the optical microfiber experienced shorter pulling distances with a maximum distance of 180µm as a result of the stretching limitation prior to the breaking of the microfiber. On the other hand, with the employment of the one-sided pulling technique, longer pulling distances can be attained due to the smaller external forces experienced by the fiber. The optical microfiber can maintain its properties up to 330µm of the pulling distance without being broken apart. By relying on this reason, it is worth to conclude that the one-sided pulling technique is more controllable than the two-sided pulling technique. In this experiment, the cladding and the core diameter as small as 1.43 µm and 0.67 µm, respectively with length of waist of 7.35 µm approximately were obtained using the one-sided pulling technique.

At the early stage of the tapering processes, the values of the transmission powers through the optical fibers were almost consistent due to the small reductions in the diameter of the cladding and core. After a few hundred microns of pulling distances, the transmission power was not stable as captured in Fig. 5 indicating the oscillations of the optical power as the fibers were pulled. Strong oscillations phenomena were observed as the value of the cladding diameter were below 2.0µm. These oscillations appeared as a result of the interference between different modes and the modulation of their envelope due to the beating of different frequency [19]. The variation of the transmission intensities during the tapering processes give an insight into the mode guiding and coupling properties of optical microfibers [20].




(a) The one-sided pulling technique




(b) The two-sided pulling technique

*Fig. 5. Characteristics of light propagation during the tapering processes.*

### *B. Effects of the geometrical properties of the optical microfibers to the transmission losses*

The optical microfibers with different taper angles at the transition regions were purposely fabricated so that light can easily be coupled into the microfiber. Fig. 6 reveals the influence of the taper angle ratio to the transmission power losses. Whilst the input taper angle is approximately one-half smaller than the output taper angle, it is observed that the optical microfiber experienced 26.09% of transmission loss. Minimum transmission loss as low as 16.03% is obtained as the values of input taper angles are greater than one-half of the output taper angle, where the ratios between the input taper angles to the output taper angles are within 0.65 to 0.80. The optical microfibers experience large transmitted power loss up to 35.39% as the values of input taper angles are slightly equal with the output taper angles (ratio of 0.90). According to Fig. 6, we suggest that the best ratio of the taper angle is 0.75 with the minimum transmission loss of 16.03%. The relationship between the taper angle ratio, $\theta_{ratio}$ and the percentage of transmission losses, $P_{loss}$ is expressed in Eq. 3 as follows:

$$P_{loss} = 275\theta_{ratio}{}^{2} - 372.6\theta_{ratio} - 143.8 \quad (3)$$

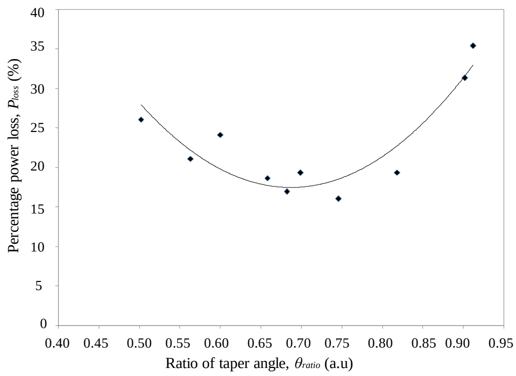



*Fig. 6. Effect of taper angle ratio to the percentage power loss.*

The critical tapered part of the optical microfiber is the output transition region because this region receives light which is transmitted from the waist region. Shorter transition length with large taper angle is important in order to minimize losses at the output part. Conversely, long taper transition can cause losses between the unstretched region and the taper waist [6].

Fig. 7 represents the effect of transition lengths ratio to the transmission power losses. The optical microfibers experience the maximum transmission losses up to 35% when the input transition lengths were shorter than the output transition lengths. As the transition length ratios lie within 1.00 to 1.28, the percentage of transmission losses decrease from 19.37% to 16.03%. The transmission losses slightly increased to 19.34% when input transition lengths are much greater than the output transition lengths, where the ratios from input to the output transition lengths are between 1.41 to 1.52. Evidently, we discover that the optimum transition length ratio is 1.27 with the transmission loss of 16.03%. The transition length was mainly affected by the taper angle. Large taper angles resulted in short transition lengths and vice versa. In order to control light to be transmitted efficiently from the input to the output of the fiber, the input taper angle should be smaller than the output taper angle. A smaller input taper angle leads to a larger transition length. As mentioned in the previous section, a smaller taper angle can be produced at the pulled end of the fiber. Meanwhile, a larger taper angle can be fabricated at the fixed end. Pulled end of the fiber will form long transition lengths with small taper angles.

Fig. 8 illustrates the effect of cladding diameters to the transmission power losses. In the first three readings, strong oscillations were observed with the highest percentage power losses up to 36%. During these oscillations, the cladding diameters obtained are within 1.43 μm to 1.80 μm. As the cladding diameters became less than 2.00 μm, the microfiber core region almost vanished which resulted in the existence of an evanescent field around the optical microfibers. It is clearly observed that the transmission power is slightly stable without strong oscillations when the cladding diameters are above 2 μm.

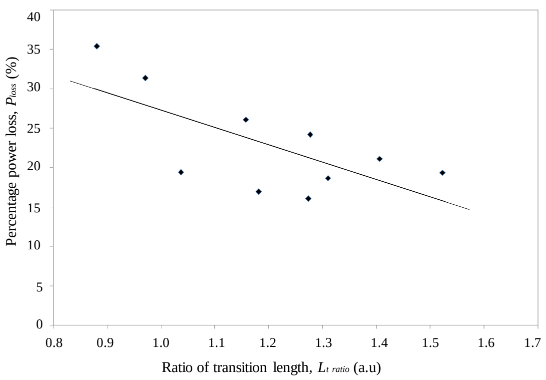



*Fig. 7. Effect of transition length ratio to the percentage power loss.*

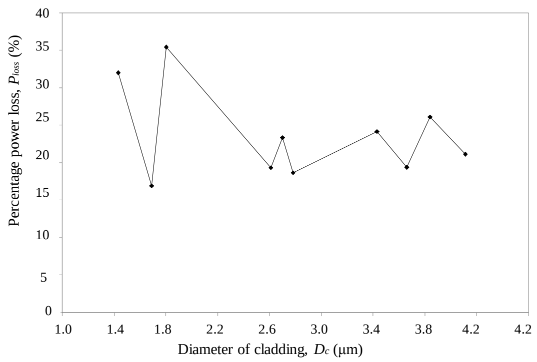



*Fig. 8. Effect of cladding diameter to the percentage power loss.*

## 4. Conclusions

This experiment discovers the potential of fusion splicer as a main tool to fabricate the optical microfiber. We reveal that the geometrical properties of the biconical fiber tapers affected the transmission power at the exit end of the optical fiber. It is proven that one-sided pulling is the preferable technique due to its capability to produce microfibers with small diameters as low as 1.43 μm. Strong oscillations occurred as the diameters of the microfibers are less than 2 μm due to the interference phenomenon between different modes. We finally conclude that the optimum ratios of the taper angles and transition lengths are 0.75 and 1.27, respectively with the percentage transmission losses for both are 16.03%.

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