Nanostructure Fusion Region of Single Mode Fiber Coupler

Dedi Irawan¹*, Fakhrudin, Z¹, Mustakim², Rian Vebrianto³, Saktioto⁴

¹ Physics Education, FKIP, Universitas Riau, Pekanbaru, Indonesia 28282
² Information System, FST, UIN Suska Riau, Pekanbaru, Indonesia 28282
³ PGMI, Fakultas Tarbiah, UIN Suska Riau, Pekanbaru, Indonesia 28282
⁴ Department of Physics, FMIPA, Universitas Riau, Pekanbaru, Indonesia 28282

*E-mail: dedi.dawan@yahoo.com

Abstract. This paper reported the characteristic of the fusion region of single mode fiber coupler. Theoretical consideration of the coupling model such as the degree of fusion and the profile of the coupling region has been investigated. The degree of fusion was inversely proportional with the separation distance between the fiber axis and the diameter of the fusion region. Fusion and elongation process also has changed the geometrical structure of the single mode fiber. FESEM image describes that the Silicon distribution was defined as a spherical crystalline which were well-dispersed. The surface of coupling region fiber coupler has the average size of the spherical-shape crystalline varies between 300 – 500 nm. However, by increasing the elongation speed and the temperature will reduce the numbers of Si per unit area, so that the density becomes fewer. It also causes the distance between the spherical shapes become longer.

Keywords: Single Mode Fiber, Fiber Coupler, Fusion Region, Degree of fusion.

1. Introduction

The use of optical system in communication has been greatly developed in past two decade. Optical system promises not only safe from human contact compared with conventional copper wire, but it also has wider bandwidth, faster data transfer, and wide range of application especially in sensor and medical application [1-4]. There are many optical component which have been fabricated and developed to support the optical system, that can be categorized as active and passive devices. Active component plays with sensor application, otherwise passive component plays with optical communication, and also becoming the supporting component of all optical system [5,6].

One of the most important passive component in optical system application is a fiber coupler. The fiber coupler has been applied to split, to combine, or to switch the optical signal. In some other case, the fiber coupler acts as directional and bidirectional depends on the need of use. The fiber coupler was fabricated by joining two or more single mode fibers based on various techniques. Fusion technique has become the best method to join it in term of power loss at the coupling region [7]. Fusion technique works under higher temperature of torch flame of 1350 °C which burn the coupling region, at the same time, the coupling region is elongates at the speed of 400nm/s and both process will be stopped automatically when the preset power ratio has been obtained [8-12]. There are many factor that induce the coupling region during fusion process. Fusion temperature, pulling speed, pulling length, and also the twisting method before positioning two or more single mode fibers on the stages.

The main parameters of the fiber coupler are stated by coupling coefficient, and the coupling ratio. These parameter have been theoretically determined based on Bassel and Hankel function than it has been compared with the theoretical empiric [13]. Based on the coupling parameter, higher accuracy
coupling ratio was easy to be obtained by just controlling the fusion temperature and pulling speed [14-17]. The investigation of the coupling region becomes necessary due to maintain the coupling parameters [18-22]. In this paper the coupling region of single mode fiber coupler after fusion and elongation process will be studied based on theoretical and experimental analysis.

2. Theoretical consideration of coupling region single mode fiber coupler

2.1 Calculation of Fusion Degree

During fusion process, the decreasing of the diameter at coupling region as depicted in Figure 1 leads to decrease the distance between fiber axis. Before it is determined, a degree of fusion is defined as the degree of core of fibers combined due to fusion and elongation. It has a value in the range between 0 to 1. The value of 0 means the fibers are only touched together as shown in Figure 1 denoted by solid black line. The core of fibers become closer as function of fusion and elongation e.g. $f = 0.5$, it is shown by red dash-line where the distance between core of fibers, $d$ is decreased to half of initial value.

The condition of the degree of fusion which equals to one is depicted by the dash blue-line. The fibers are completely joined and it can be assumed as a circular form. Since the cross section of the coupling length is considered as an ellipse which has two major axis, the distance between the fiber center is $d = D\left(\sqrt{2} - 1\right)$. Where $D$ is the diameter of the core of fiber after fusion which can be measured.

![Figure 1. Various degree of fusion as function of separation of fiber axis](image)

If the initial diameter of coupling region before joint is $D_0 = 2b$, and $d$ is the separation between fibers axis, the degree of fusion, $f$ can be expressed mathematically as follows.

$$f = \frac{1}{2 - \sqrt{2}} \cdot \frac{d}{D_0 \left(2 - \sqrt{2}\right)}$$  \hspace{1cm} (1)

It can be rearranged in term of the distance of separation of fiber axis.

$$d = D_0 \left(1 - f \left(2 - \sqrt{2}\right)\right)$$  \hspace{1cm} (2)

The calculation of degree of fusion is carried out using a flowchart given by Appendix C. The value of $D_0 = 2b$ is taken from the experimental data.

2.2 Coupling Diameter Profile

When the directional fiber coupler fabricated by heating and concurrently pulling both sides of the coupling region 800 – 4500 µm with elongation speed of 100 µm/s. The heating and pulling process stretch the coupling region and cause the geometrical structure of fiber structure changed. The
significant geometrical change can be seen at cross section coupling region. After fusion, the diameter profile of coupling region is characterized to be three parts as depicted in Figure 2.

![Figure 2 Geometrical coupling region.](image)

Figure 2 Geometrical coupling region, $l_c$ is the critical region, $l_\Delta$ is left and right tapered region, and $\Delta l$ is the fusion zone.

The diameter, $D$ varies along the coupling region $\Delta l$, as depicted in Figure 2. The left and right taper regions are labeled by $l_-$ and $l_+$ respectively. If the length of fiber is considered in $z$ direction, the variation of cross section diameter at taper region can be mathematically expressed as follow.

$$\nabla \cdot D = \frac{D}{\Delta l}$$

(3)

$$dD = \frac{D}{\Delta l} \Rightarrow \frac{dD}{D} = \frac{1}{\Delta l} dz$$

(4)

$$\int \frac{dD}{D} = \frac{1}{\Delta l} \int dz$$

(5)

$$\ln \frac{D}{D_o} = \frac{1}{\Delta l} l$$

(6)

$$D(l) = D_o \exp \left( \frac{l}{\Delta l} \right)$$

(7)

By assuming the left of taper region is symmetric with the other right one, the diameter profile of coupling cross section at coupling region can be written as follows.

$$D_{cl}(l) = D(l_-) + l_c + D(l_+)$$

$$D_{cl}(l) = \left[ D_o \exp \left( \frac{l_-}{\Delta l} \right) \right] + l_c + \left[ D_o \exp \left( \frac{l_+}{\Delta l} \right) \right]$$

(8)

3. Coupling region analysis by FSEM

The field emission scanning electron microscope (FSEM) is used to characterized the effect of the fabrication process to the structure of the silica material of single mode fiber at the coupling region

3. Results and Discussion

Fusion and elongation in fabrication process of fiber coupler change the structure and geometry of initial single mode fiber. Physically it reduces the diameter profile of coupling cross section, refractive index, and the propagation constant. It also changes the distribution of silica at the cladding surface in the coupling length [23-24]. Fusion and elongation give significant effect to the change of diameter profile at coupling region cross section. Experimental result shows that it varies exponentially along the coupling region and makes a taper profile.
The physical stress in the coupling region is induced by the thermal and geometrical change. Since the torch flame heats the coupling region, while the pulling stages pull it in micro meter scale, this process reduces gradually the diameter of fiber cross section. Since the flow rate of H₂ gas is carefully controlled to obtain nearly stable torch flame with a required temperature distribution in the coupling region area, the diameter of coupling length will vary along the coupling region following the theoretical profile given by Equation (4), and it will result a uniform propagation constant among the fibers.

The diameter profile is also theoretically modeled as shown in Figure 3. It exhibits the three region of $D(l_0)$, $D_0$, and $D(l_i)$ 1X3 fiber coupler. The tapered regions of $D(l_0)$ and $D(l_i)$ show that the diameter is decreased from the initial diameter 250 µm to 35 µm which is defined as the diameter of coupling length.

![Figure 3 Theoretical calculation of diameter profile of the fiber coupler](image)

The geometrical properties of coupling region are described by the degree of fusion [25]. Since the distance between the cores becomes closer and closer as function of pulling and heating process, the value of fusion degree is also going to the maximum until it makes a circular term as given by Equation (1) and Equation (2). Based on these equations, the modeling result as shown in Figure 4 depicts that the degree of fusion is inversely proportional with the separation distance between fiber axis. This means that by increasing the degree of coupled fiber heating and pulling, the separation distance between cores become closer.

However, the fabrication of directional fiber coupler cannot be exactly carried out until the distance between the fibers’ core is reduced to zero due to cladding medium. Modeling results also consolidates that by reaching maximum numbers of degree of fusion reduces the distance between fiber axis until it is equal to 16.3 µm. If the average cores radius after fusion is identical and equal to 4.8 µm, the distance between cores is equal to 7.6 µm which defined as a composite region between cladding.
In three dimensions the effect of fusion on coupling cross section and separation between fiber axis is shown in Figure 5. It can be seen that by increasing the degree of fusion, pulling and heating process reduce not only the distance between fiber axis, but also the diameter of coupling length.

The effect of fusion and elongation process is not only on the physical structure, but it also changes the surface of the coupling region. If the jacket of SMFs is clearly removed before fusion utilizing the ethyl alcohol, the surface of cladding will be smoother as shown in Figure 6. However, thermal and geometrical stress slightly affects the atomic bonding of Silicon Dioxide.
Basically, the SMFs consist of pure silica glass $\text{SiO}_2$ as the cladding with diameter 125 µm, and the center is doped by Germanium Dioxide $\text{GeO}_2$ as the core with diameter about 8.2 µm. The atomic bonding between Silicon and Oxygen is a symmetric bonding O–Si–O.

High fusion temperature cannot be stopped suddenly; it has a take time for going down from 1350 °C to 27 °C. This causes Silica (Si) growth on the surface of the coupling region. In addition, the environment also transfers heat into dielectric fibers. As consequently, Silicon cannot be perfectly rebounded with Oxygen as before fusion. After fusion process, Silicon distribution is defined as a spherical crystalline which were well-dispersed. Figure 7(a) exhibits the surface of coupling region of 1X3 fiber coupler with average size of the spherical-shape crystalline varies between 0.3 – 0.5 µm.

However, by increasing the elongation speed and temperature will reduce the numbers of Si per area, so that the density becomes fewer. It also causes the distance between the spherical shapes to be longer. It can be seen in Figure 7(b) that the distance between the crystalline of 1X3 directional fiber coupler fabricated at temperature 1200 °C is further that of one fabricated at temperature 1350 °C. It also has a longer molecular distance varies between 0.5 µm to 2 µm and well dispersed.

The change of chemical structure at coupling region will induce the performance of power fiber coupler. The germanium at core diffuses to the fiber’s cladding. Certainly this diffusion phenomenon will also change the characteristics of fiber’s cladding. In other word, the refractive index of core and cladding at coupling region is slightly changed for a temperature change in range of 27 – 1350 °C.
4. Conclusion
The geometrical structure of the coupling region varies exponentially as function of the coupling length. Good agreement between the degree of fusion with the separation distance between fiber axis was obtained. The diameter of the coupling region after fusion process was reduced until 125 micron meter. However, the elongation and heating process change the structure of silica fiber. The germanium at core diffuses to the fiber’s cladding. Certainly this diffusion phenomenon will also change the characteristics of fiber’s cladding. FESEM image describes that the Silicon distribution was defined as a spherical crystalline which were well-dispersed. The surface of coupling region fiber coupler has the average size of the spherical-shape crystalline varies between 300 – 500 nm

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