Quantum Interpretation of Light Normalization at the Coupling Region Single Mode Fiber Coupling

Dedi Irawan, Saktioto

Physics Education – FKIP, Universitas Riau
Physics, Faculty of Mathematics and Natural Science – FMIPA, Universitas Riau
Jl. HR. Soebrantas, Km. 12.5, Pekanbaru, 28293, Indonesia

E-mail. dedi.dawan@yahoo.com  E-mail. saktioto@yahoo.com

Abstract. This paper describes light normalization phenomenon as a quantum interpretation at the coupling region optical fiber coupler. Two single mode fibers (SMF) were successfully fabricated together based on fusion method at heating temperature of 1350°C and stopped automatically when the pre-set coupling ratio of 50% and 50% obtained. During fusion process, 1 mW laser diode was inserted to the one of the two input ports, and it was gradually transferred to the second fiber as function of the coupling coefficient. The properties of light intensity in term of electromagnetic wave also was determined based on quantum mechanics theory by utilizing Bassel and Hankel’s functions. The results show that the composite fiber has higher normalization propagation constant than other fiber for wavelength below 1320 nm. It found that to get lossless fiber coupler the wavelength operation should be below than 1320 nm so that few powers at cores transferred and propagated at the cladding.

1. Introduction

The development of optical devices in past two decades was greatly expanded in various area such as for the communication, data intelligent, image processing and also sensor application. Single mode fiber (SMF) coupling is one of many passive devices that plays dominant use in all light optic application. It was developed based on power transfer as a light interaction in the fiber coupler [1-4].

Snyder (1983) determined the function of electromagnetic wave propagating along the single mode fiber coupler. A set of transformation matrix was utilized to model the transfer power between 2X2 fiber [6]. Few years letter, another method to model power exchange among two fibers was also introduced. The Kinetic model was formulized and it showed that the power transfer significantly depends on the coupling coefficient and the coupling ratio. In that study, the theoretical coupling coefficient was compared between the empirical coupling coefficient. As the results, it was noticed that the preset coupling ratio was slightly difficult to be maintain during fusion process [7-8].

The fabrication of the fiber coupler with M input and N output such MXN was previously studied [9-10]. This study shows that the theoretical method of power transfer based on the matrix MXN has a good agreement with the experimental results. The Coupling parameters, which induce the coupling coefficient and the coupling ratio, were also investigated [11]. Higher accuracy coupling ratio was obtained by determining the geometrical characteristics, the degree of fusion, and the function of the refractive index [12].
Since the coupling ratio is a function of the coupling coefficient, of course, the coupling coefficient has become the most important parameters for the fiber coupling. The used of Bessel and Modified Bessel function was used to determine the coupling coefficient between the fibers [13]. The results of that study showed that the coupling coefficient has follow the empirical one from the experimental study with good agreement both for all distance between the fiber axis. However, light propagating at the coupling region follows the Total Internal Reflection (TIR) principle, so that the intensity of light must be normalized [13-14]. This becomes interesting to investigate the normalized propagation constant due to fusion process and laser effect.

2. Fabrication of the Fusion Fiber Coupling.
Single Mode Fiber Coupling is fabricated by using Acoupler2000 Machine. This technology work under fusion method. Two or more single mode fibers are twisted together and positioned at the pulling station. The initial step of the fabrication is to set the coupling ratio then to set up the type of wavelength, temperature and also to set the position of the flame as the heating source. After setting the parameters, the fabrication is begun by just pressing the start button. The twisted area will be heated at preset temperature (1350°C) and it will stop automatically when the preset coupling ratio obtained.

3. Theoretical Consideration of Quantum Interpretation of Light Normalization at the coupling region
The coupled mode equation has been derived for the multi fiber coupler which consists of multi fibers joint [9,11]. Since the propagation of electric fields in both fibers are assumed as an ideal condition with no optical loss, power at both fibers are normalized per element area $dA$ [5].

$$N = \int_{A_x} |\Psi(x,y)|^2 dA$$

(1)

By remembering vector $e_{1x}$ and $e_{2x}$, are the electric fields at fiber 1 and fiber 2 respectively, the normalization can be written as a power flow to the unity. First, the normalization of power in fiber 1 relative to the fiber 2 is expressed as follows.

$$N_1 = \frac{1}{2} n_1 Y_0 \int |e_{1x}|^2 dS$$

(2)

The propagation of electric field in single mode fibers is normalized since total internal reflection completely occurred. If the input power is launched into fiber one only, this electric field will be transferred to the nearest fiber such as fiber two. This electric field is then polarized into $x$ and $y$ axis. By assuming the field is polarized into $x$ coordinate, the transverse field components are written as follow.

$$e_{1x} = \begin{cases} \frac{C_1 [J_1(u_1 r_1) / J_1(U_1)] \cos \phi_1}{C_1 [K_0(w_1 r_1) / K_0(W_1)] \cos \phi_1}, & r_1 < a_1 \\ \frac{C_1 [K_0(w_1 r_1) / K_0(W_1)] \cos \phi_1}{C_1 [J_1(u_1 r_1) / J_1(U_1)] \cos \phi_1}, & r_1 > a_1 \end{cases}$$

(3a)

$$e_{2x} = \begin{cases} \frac{C_2 [J_0(u_2 r_2) / J_0(U_2)] \cos \phi_1}{C_2 [K_0(w_2 r_2) / K_0(W_2)] \cos \phi_1}, & r_2 < a_2 \\ \frac{C_2 [K_0(w_2 r_2) / K_0(W_2)] \cos \phi_1}{C_2 [J_0(u_2 r_2) / J_0(U_2)] \cos \phi_1}, & r_2 > a_2 \end{cases}$$

(3b)

where $C_1$ and $C_2$ are constants, and $J_0$ and $J_1$ are first kind of Bessel function. $K_0$ and $K_1$ are Hankel function (the second kind of modified Bessel functions). Others constants involved in the calculations are given as follow [15] (Khare, 2002).

$$U_1 = u_1 a_1 = \kappa_0 a_1 \sqrt{n_1^2 - \beta_{11}^2}$$

(4a)

$$U_2 = u_2 a_2 = \kappa_0 a_2 \sqrt{n_2^2 - \beta_{01}^2}$$

(4b)

$$W_i = w_i a_i = \kappa_0 a_i \sqrt{\beta_{ii}^2 - n_0^2}$$

(4c)
$$W_z = w_z a_z = \kappa_0 a_2 \sqrt{\beta_{01}^2 - n_0^2} \quad (4d)$$

where $\beta_{01} = \beta_1 / \kappa_1$ and $\beta_0 = \beta_0 / \kappa_0$ are the expression representing the propagation constant of fundamental modes at core and coupling length respectively. Now, by substituting Equation (3a) into Equation (2) yields:

$$N_1 = \frac{1}{2} n Y_0 \int_0^2 \cos^2 \varphi \frac{d \varphi}{\beta^2} \left[ \int_0^2 J_1^2(u_{1r}) r_1 dr_1 + \int_2^\infty K_1^2(w_{1r}) r_1 dr_1 \right]$$

This equation can be solved by using integral identity as follow [16]

$$K_1(z) = \frac{z}{2} \left( K_2(z) - K_0(z) \right) \quad (6)$$

$$J_1(z) = \frac{z}{2} \left( J_2(z) - J_0(z) \right) \quad (7)$$

By substituting Equation (7) and Equation (6) into Equation (2) yields,

$$N_1 = \frac{1}{2} \left( n Y_0 \pi a_1^2 \right) K_0(W_1) K_2(W_1) \left( \frac{V_1}{U_1} \right)^2 \quad (8)$$

This Equation describes that the electric field propagating at fiber 1 is normalized which proportional to the fiber radius and the normalized frequency. Similarly, the normalization of electric field in fiber 2 is obtained as follows.

$$N_2 = \frac{1}{2} \left( n Y_0 \pi a_2^2 \right) K_0(W_2) K_2(W_2) \left( \frac{V_2}{U_2} \right)^2 \quad (9)$$

The calculation of normalization of electric field at coupling region is started by inserting the initial values of parameters such as refractive index, and core radius. The constants of first and second kind of Bessel function are then calculated. The operational wavelength is varied and the change of normalized propagation constant is visualized. The normalization is then calculated as a function of diameter of the coupling cross section.

4. Results and Discussion

4.1 Power Transfer between Two Single Mode Fiber

The fabrication process of directional fiber coupler was designed as automatic control which all mechanical motion and output power characteristics are recorded by an integrated acquisition card installed in the computer system. All coupling and fusion parameters such as pulling speed, fusion temperature or gas flow, coupling ratio, coupling length, and torch flame position could be set up before fusion and elongation was started. Basically, the initial input parameters given by Table 1 are used to model power exchanges between the fibers at coupling region.

| Table 1 Physical parameters of power exchanges in multi directional fiber coupler |
|---------------------------------|-----------------|
| SMF Parameters | Value |
| Core refractive index, $n_{c0}$ | 1.4677 |
| Core refractive index, $n_{c1}$ | 1.4624 |
| Input power amplitude, (mW) | 1 |
| Wavelength of input signal, (nm) | 1310 |
| Coupling coefficient, $\kappa$ (mm) | 1.5 |
| Step: interval coupling region, $z$ (m) | $0.1 \times 10^{-6} - 7.5 \times 10^{-6}$ |
| Core diameter, $a$ (µm) | 8.2 |
The power exchanges among fibers during fabrication process are experimentally exhibited as a function of pulling time. It can be seen in Figure 1a that the fiber coupler with coupling ratio 50:50 is fabricated by heating two SMFs. As the heating process is started, while the coupling region is also pulled, the initial power shown by red line is detected in fiber 1. When the fusion and elongation are increased, the fibers become melting. The cladding of fiber 1 and fiber 2 are joined, and the distance between the cores becomes closer. At this condition, the coupling coefficient is exponentially increased.

When the coupling region is more pulled, power in fiber 1 is exponentially decreased, and transferred to fiber 2. This power exchange was automatically stopped when the preset coupling ratio is attained. Since the coupling region is carefully twisted, pulled and heated with the suitable parameters, the pre-set coupling ratio will be obtained with high accuracy. Otherwise, inappropriate parameters cause the fabrication process stopped when the preset coupling ratio is slightly changed. The modeling has been purposed by constructing a matrix transfer of 2X2 which it can be written as follows.

\[
\begin{bmatrix}
A_1(z)
\end{bmatrix} = \begin{bmatrix}
\cos \sigma z - j \frac{\delta}{\sigma} \sin \sigma z & -j \frac{K_{21}}{\sigma} \sin \sigma z \\
- j \frac{K_{12}}{\sigma} \sin \sigma z & \cos \sigma z - j \frac{\delta}{\sigma} \sin \sigma z
\end{bmatrix}
\begin{bmatrix}
A_0(0)
\end{bmatrix}
\]  

By inserting the initial parameters given in Table 5.1, and input power launched to the fiber 1, the transfer matrix component of Equation (5.1) is yielded as follows.

\[
M_{2\times2} = \begin{bmatrix}
1.0000 - 0.0000i & 0 - 0.0112i \\
0 - 0.0112i & 1.0000 + 0.0000i
\end{bmatrix}
\]  

This matrix exhibits as transfer power between fiber 1 and fiber 2. Rows and columns of this matrix describe the condition of power at the coupling and the number of n-th fibers. If the first column is revealed as the fiber 1, and the second column is revealed as the fiber 2, it is clear that the first row indicates power at initial condition when the input power is launched into fiber 1, while power at fiber 2 is a minimum. The power exchange is being preceded by calculating the iteration of the inner matrix until the final condition where the maximum power at fiber 2 is denoted by the second row of that matrix. As the results, good agreement between modeling and experimental results of power exchanges between fibers in 1X2 fiber coupler is depicted in Figure 1 (a and b).

![Figure 1](image.png)

**Figure 1.** Power exchanges in 1X2 fiber coupler, a) Experimental results with pulling speed = 150 µm/s, EL1 = 0.31 dB. b) Theoretical results
It can be evidently seen in Figure 1(a) that the input power is gradually transferred from fiber 1 to fiber 2 as a function of the pulling time which is also visualized during fusion. Since pulling time is defined as the time which is recorded during heating and pulling processes and by knowing the elongation speed, the pulling length can be determined. Modeling of power exchanges between fiber 1 and fiber 2 is then carried out as function of pulling length as depicted by Figure 1(b). A good approximation of power exchanges between modeling and experimental results shows that power in fiber 1 is periodically transferred to fiber 2. Here, the fiber coupler of 1X2 is considered having the coupling ratio 50:50.

4.2 Light Normalization at the coupling region of Single Mode Fiber Coupling

The structure and properties of single mode fibers at coupling region change due to fusion and elongation. Of course this effect influences the constant of power propagation in the fiber glass medium. In this following explanation, the change of propagation constant is presented as function of operational wavelength.

Since the coupling region consists of two or more single mode fibers, and the refractive index after fusion are 1.4568 and 1.4628 for input fiber and others coupled fibers respectively, the gradient change of both normalized propagation constant is nearly equivalent. But, it remains gradually decreases with lower gradient than both fibers. This due to low uniformity of coupling region structure disturbs the medium. It can be seen that normalized propagation constant of fiber 1 is higher than fiber 2 and nth fiber.

Since the refractive indices are slightly changed after fusion, the constant of light propagation will be also changed. Figure 2 shows the normalized propagation constants of light in SMF fiber, LP01 and in the composite fiber at the coupling region, LP11. It can be seen that the normalized propagation constant of fiber 1, which propagates the power before it is transferred, is higher than the normalized propagation constant in the others fibers. This is caused by the fiber 1 acted as the predominant fiber when they are joined during fusion. This means others fiber will be collected at surrounding fiber 1.

Figure 2. Normalization constant varies with optical wavelength.

Figure 2 also depicts that the composite fiber has higher normalization propagation constant than other SMF fiber for wavelength below 1320 nm as denoted by dash blue line and red line respectively. It is gradually decreased with increasing the wavelength. However, it can be identified that it equal to the normalized propagation constant of nth core due to smaller gradient at wavelength 1320 nm.
it can be summarized that to get lossless fiber coupler the wavelength operation should be below than 1320 nm so that few powers at cores transferred and propagated at the cladding. In other word, if it is higher than 1320 nm power transferred to the cladding cannot go through to the fibers core. Note, in this calculation the initial wavelength used during experiment is 1310 nm.

5. Conclusion
Power transfer among the fibers has been investigated during fusion process and it has given a good agreement between theoretical and experimental work. However, This good results was obtained by introducing and determining the normalization propagation constant among the fibers. The normalization was varied as a function of the wavelength operation. In conclusion, to get lossless fiber coupler the wavelength operation should be below than 1320 nm so that few powers at cores transferred and propagated at the cladding

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