Advanced Studies in Theoretical Physics
Vol. 9, 2015, no. 10, 475 - 482
HIKARI Ltd, www.m-hikari.com
http://dx.doi.org/10.12988/astp.2015.5338

Theoretical Improvement of Coupling Parameters Directional Fiber Coupler Using Bessel Function

Dedi Irawan

Industrial Engineering, Faculty of Science and Technology
UIN Suska Riau, Pekanbaru 28282 Indonesia

Petir Papilo

Industrial Engineering, Faculty of Science and Technology
UIN Suska Riau, Pekanbaru 28282 Indonesia

Rika Taslim

Industrial Engineering, Faculty of Science and Technology
UIN Suska Riau, Pekanbaru 28282 Indonesia

Muhammad Ikhsan

Industrial Engineering, Faculty of Science and Technology
UIN Suska Riau, Pekanbaru 28282 Indonesia

Toto Saktioto

Physics Depart. Faculty of Mathematics and Natural Science
University of Riau, Pekanbaru 28282 Indonesia

Abstract

We have investigated the optimum parameter to fabricate multi fiber of silica material for directional coupler based on fusion and elongation techniques. Coupling coefficient between the fibers was derived by using Bessel function.

However, the fusion temperature was experimentally determined as function of elongation speed. Good performance of multi fiber coupler has been obtained for fabrication parameters of fusion temperature and elongation speed of 1350 ^{o}C and 125 μm/s respectively. The proposed coupling coefficient shows a better accuracy with empirical one for various coupling length. It is exponentially increased by reducing the distance between fibers. Finally, the microscopic analysis of coupling region deformation has shown that the silica material was well dispersed and distributed.

Keywords: Coupling Coefficient, Bessel Function, Fusion temperature and Elongation speed

1 Introduction

Optical multi fiber coupler plays important key in optical network communication. It's ability to process whatever to divide, to combine, and to switch any optical signal makes this device more applicable as passive devices and sensing application [1, 2]. The multi fiber coupler was fabricated by joining at least two optical fibers until the fiber's cladding make a contact and allow the electromagnetic field interact each other. The multi fiber coupler was experimentally studied based on the energy exchange among guided modes [3, 4]. He also theoretically determined a coupling Eq. from unperturbed general wave Eq.. A derivation of his general theory was followed by the application to the specific cases of electro optic modulation, photo elastic and magneto-optic modulation, and optical filtering. Fabrication process to produce multi fiber couplers requires an advance technique since it deals with small SMF having the diameter in micron size. Danh *et al.* purposed a twist-etching method that successfully fused two single mode fibers by potting the coupling region. The twisted-coupling region was solidified by filling a bottle and then two fibers were positioned with certain index oil. It was simplified with a liquid state potting material. But, this technique still produces a fiber coupler with high insertion and exertion loss about 20 dB [5].

A few years later, a new method to fabricate fiber coupler with a better performance was studied [6]. His method was called fusion, which is carried out by comparing the manual and automatic techniques. The steps of fabrication was started by removing the fiber coating, fiber setting at the connector and installed in the workstation. The coupling region was heated until the desired coupling ratio was reached. Nevertheless, this method still has a lot of limitations in terms of maintaining the coupling ratio since it looks like a trial-and-error fabrication system. It more emphasizes to the polarization maintaining fiber. This technique produced the fiber couplers with exertion loss less than 0. 5 dB. The fabrication of multi fiber coupler was improved from a conventional becomes more advance technique in period of time. Fusion method was improved by changing the plasma source by utilizing CO_2 laser [7]. Good performance of fundamental 1X2 fiber coupler was fabricated by a suitable fusion period. This method still has significant limitation of experimental set up, because the process contaminates the structure of SiO_2 silica fiber due to the chemical reaction between higher temperature CO_2 laser and the silica fiber. It may also change the properties of SiO_2 fiber, instead of high-cost fabrication technique.

In this paper, we optimize the design of the multi fiber coupler by using fusion and elongation method. The coupling parameters and power transfer propagation at coupling region are determined based on Coupled-Mode Theory (CMT) and perturbation method. However, the accuracy of coupling coefficient is improved by introducing Bessel and modified Bessel function in derivation. We also provide the appropriate heating temperature and pulling speeds to produce good performance of fiber coupler in term low optical loss.

2 Fabrication Technique of Multi Silica Directional Fiber Coupler

The fabrication of multi fiber coupler is carried out by placing three single mode fibers on the stages. Corning fiber (SMF-28e®), are connected to the laser source (1310 nm) and displayed to the photo detector. The two fibers are twisted and held by a vacuum system in both stages. All components are recorded and by a data acquisition card installed to the computer system. The initial step is to set parameters such as coupling ratio, maximum pulling length, x-y-z position of torch flame, and flowing of H_2 gas. 1 mW laser launched to the one of input ports is detected by photo detector and kept for calibration. At the same time, fusion and pulling process are started. During torch flame heating the coupling region, the fibers are elongated by pulling stages with suitable pulling speed. Heating and pulling process will be automatically stopped when the pre-set coupling ratio is reached.

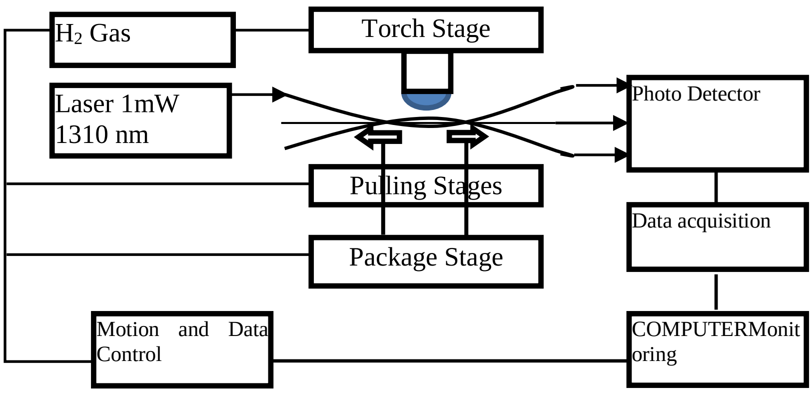

Fig 1. Experimental set up to fabricate fiber coupler

3 Coupling Parameters of Fused Fiber Coupler

A. Optimum coupling coefficient

Since the fibers having identical propagation constants are electromagnetically isolated, they will transfer their power each other due to coupling coefficient between them. The coupling coefficient can be expressed as follow [4].

$$\kappa_{ij} = \frac{\omega\varepsilon_0}{4}\int_S (n_c^2 - n_1^2)\mathbf{e}_{1x}\cdot\mathbf{e}_{2x}^*\ dS \tag{1}$$

The electric fields in both fibers are varies exponentially, and it was summarized by [4, 5],

$$\mathbf{e}_{1x} = \begin{vmatrix} C_1\left[J_1(u_1r_1)/J_1(U_1)\right]\cos\varphi_1, & \mathrm{r}_1 < a_1 \\ C_1\left[K_1(w_1r_1)/K_1(W_1)\right]\cos\varphi_1, & \mathrm{r}_1 > a_1 \end{vmatrix} \tag{2a}$$

$$\mathbf{e}_{2x} = \begin{vmatrix} C_2\left[J_0(u_2r_2)/J_0(U_2)\right]\cos\varphi_1, & \mathrm{r}_2 < a_2 \\ C_2\left[K_0(w_2r_2)/K_0(W_2)\right]\cos\varphi_1, & \mathrm{r}_2 > a_2 \end{vmatrix} \tag{2b}$$

where C is constant coefficient that related to the normalization of electric field $C = \left(1/\sqrt{N}\right)$, and J_0, J_1 are the first kind of Bessel function. K_0 and K_1 are the second kind of modified Bessel function. And $U_1 = u_1a_1 = \kappa_0 a_1\sqrt{n_1^2 - \bar{\beta}_{11}^2}$. Where $\bar{\beta}_{11} = \beta_{11}/\kappa_0$ and $\bar{\beta}_{01} = \beta_{01}/\kappa_0$ are the expression denoted as propagation constant of LP_{01} and LP_{11} respectively. The wave number k is inversely proportional with wavelength, $k_0 = 2\pi/\lambda$. By substituting Eq (2) in to Eq (1) yields.

$$\frac{1}{\sqrt{N_1N_2}}\int_0^{a_2}\int_0^{2\pi}\frac{J_0(u_2r_2)}{J_0(U_2)}\frac{K_1(w_1r_1)}{J_0(W_1)}\cos\varphi_1 r_2 dr_2 d\varphi_1 \tag{3}$$

To solve (3), coordinate (r_1,φ_1) as field in fiber 1 has to be transformed in term of coordinate (r_2,φ_2). It can be done by using transform method given by reference [1].

$$K_{m(ar_1)}\begin{vmatrix}\cos m\varphi_1 \\ \sin m\varphi_1\end{vmatrix} = \pm\sum_{p=-\infty}^{+\infty}(-1)^p K_{m+p}(ad)I_P(ar_2)\begin{vmatrix}\cos p\varphi_2 \\ \sin p\varphi_2\end{vmatrix} \tag{4}$$

In this case, the calculation of coupling coefficient is done on the fundamental fiber couplers, so $m = 1$ and $a = (W_1/a_1)$. By substituting in to (4), it can be written as follow.

$$\underbrace{\sum_{p=-\infty}^{+\infty} (-1)^p \frac{K_{1+p}(w_1 d)}{J_0(U_2)K_1(W_1)}}_{1} \int_0^{a_2} \underbrace{I_P(w_1 r_2) J_0(u_2 r_2) r_2}_{2} \underbrace{\int_0^{2\pi} \cos p\varphi_2 d\varphi_2 dr_2}_{3} \tag{5}$$

From part 3 of (5) it can be seen that,

$$\sum_{p=-\infty}^{+\infty} \int_0^{2\pi} \cos p\varphi_2 d\varphi_2 = \left| \begin{array}{lll} 0 & \text{if} & p = \pm 1, \pm 2, \ldots \pm \infty \\ 2\pi & & p = 0 \end{array} \right. \tag{6}$$

To solve part 2 of (5) which has different kind of Bessel Function, can be done by using Bessel relation as follow [6],

$$\int z J_0(az) I_0(bz) dz = \frac{z}{a^2 + b^2} \left[b J_0(az) I_1(bz) + a J_1(az) I_0(bz) \right] \tag{7}$$

Now, it yields.

$$\int_0^{a_2} J_0(u_2 r_2) I_0(w_1 r_2) r_2 dr_2 = \frac{a_2}{\left(\frac{U_2^2}{a_2^2} + \frac{W_1^2}{a_1^2} \right)} \left[\frac{W_1}{a_1} J_0(U_2) I_1(w_1 a_2 / a_1) + \frac{U_2}{a_1} J_1(U_2) I_0(w_1 a_2 / a_1) \right] \tag{8}$$

Then, by substituting Equation (8) in to Equation (5), and using boundary given by (12), the coupling coefficient between two fibers can be written as following Equation.

$$\kappa_{12} = \left[\frac{2(n_2^2 - n_1^2)}{n_1 n_2} \right]^{1/2} \frac{K_1(w_1 d)}{K_1(W_2)\sqrt{K_0(W_1)K_2(W_1)}} \frac{U_1 U_2}{a_1 V_1} \frac{1}{U_2^2 + \bar{W}_1^2} \left[\bar{W}_1 K_0(W_2) I_1(\bar{W}_1) + W_2 K_1(W_2) I_0(\bar{W}_1) \right] \tag{9}$$

It can be seen in Fig 2 that the purposed model of coupling coefficient is more accurate that previous one again empirical. When the fiber separation is longer, the purposed coupling coefficient more decreases following the experimental one compared to the previous coupling model.

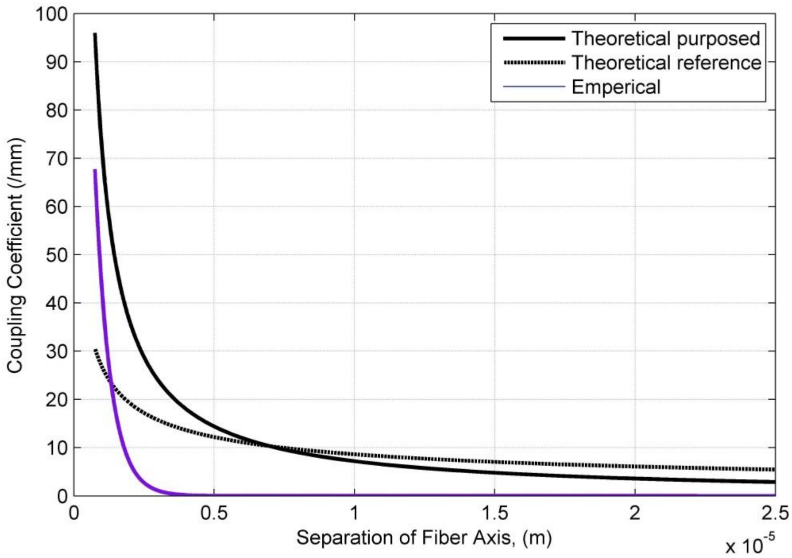

Fig 2. Coupling coefficient versus separation between fiber axis

B. Fusion and Elongation Parameters

All optical devices require the power loss as minimum as possible. In the case of multi multi fiber coupler, the performance of output power characteristics is also determined by the exertion loss. It commonly appears when fabricating the fiber coupler. Unlike the coupling length, the degree of fusion can be controlled by varying the temperature of the flame and the speed of the fiber elongation. The elongation speed, which induces strain in the coupled fibers, is adjusted by changing the power driven of the motors attached to the translational pulling stages. The minimum strain is required to be introduced during the fusion stage that should be sufficient to avoid any sagging of the softened pair of fibers due to gravity. By manipulating the temperature of the fibers, varying the fiber's location relatively to the flame, the time of fusion phase, and the speed of elongation mainly any degree of fusion can be achieved in practice. The degree of fusion corresponding to the length of elongation determines the separation distance between fiber axis at the coupling region. However, by twisting three or four fibers at the fusion region will make the pulling stages directly elongate the coupling region. It can be seen that the minimum of exertion loss of 1X3 and 1X4 fiber coupler can be reached at the same elongation speeds. It can be seen in Fig 3 that the lowest value of exertion loss in 1X3 fiber coupler is yielded 0.34 dB at pulling speed of 100 μm/s.

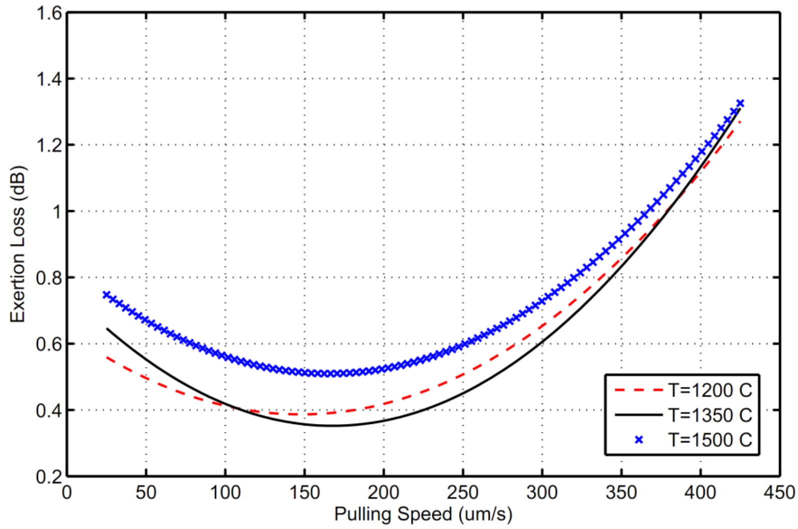

Fig 3 Exertion loss of fiber coupler change as function of pulling speed for fiber coupler 1X2, 1X3, and 1X4

The lowest exertion loss of 1X4 was obtained 0.34 dB by pulling the coupling region at elongation speed of 125 µm/s at fusion temperature 1350 °C as given in Fig 3. Certainly, these appropriate values of pulling speed are very important to obtain better fabrication technique for various single mode fiber couplers. Fig 3 exhibits that the exertion loss of 1X4 is higher than 1X3 fiber couplers. The more number of fibers joint, the more elongation of the coupling region is required to increase the degree of fusion so that power can be transferred. The further the coupling length causes more losses of optical power at coupling length. It is also caused by the change of fiber's refractive index during pulling and heating process.

Conclusion

This study summarizes that the power transfer propagation of electric field at the coupling region is significantly affected by the distance of separation between the fibers and also the coupling length. The coupling coefficient was exponentially increased by reducing the distance of separation between fiber axes. The profile of coupling ratio as function of the pulling length provides an information that a set of pre-set coupling ratio can be easily obtained at shorter pulling length. Therefore, the lowest exertion losses are about 0.003 dB have been produced for the pulling speed of 125 µm/s at heating temperature of 1350°C.

Acknowledgements. We would like to thank the Faculty of Science and Technology UIN Suska Riau which support this research project.

References

[1] J. R. Guzman-Sepulveda, V.I. Ruiz-Perez, M. Torres-Cisneros, J.J. Sanchez-Mondragon, D.A. May-Arrioja, Fiber optic sensor for high-sensitivity salinity measurement, *IEEE Photonics Technology Letters*, 25 (2013) 2323-2326. http://dx.doi.org/10.1109/lpt.2013.2286132

[2] D. Irawan, Saktioto, J. Ali, Defrianto, Breakdown Voltage Effect on coupling Ratio Fusion Fiber Coupling, *Physics Procedia*, 19 (2011) 477-481. http://dx.doi.org/10.1016/j.phpro.2011.06.195

[3] B. E. Little, W.A. Huang, Coupled-Mode Theory for Optical Waveguide, *Progress in Electromagnetic Research*, 10 (1995) 217-270.

[4] A. Yariv, Coupled-mode theory for guided-wave optics, *Quantum Electronics*, IEEE Journal of, 9 (1973) 919-933. http://dx.doi.org/10.1109/jqe.1973.1077767

[5] T. Danh, K. Kee, S. Sang, Single-mode fiber directional couplers fabricated by twist-etching techniques (stabilization), *Quantum Electronics, IEEE Journal*, 17 (1981) 988-991. http://dx.doi.org/10.1109/jqe.1981.1071205

[6] I. Yokohama, J. Noda, K. Okamoto, Fiber-coupler fabrication with automatic fusion-elongation processes for low excess loss and high coupling-ratio accuracy, *Lightwave Technology, Journal of*, 5 (1987) 910-915. http://dx.doi.org/10.1109/jlt.1987.1075597

[7] C. McAtamney, A. Cronin, R. Sherlock, G.M. O'Connor, T.J. Glynn, Reproducible Method for Fabricating Fused Biconical Tapered Couplers Using a CO2 Laser Based Process, *Proceedings of the Third International WLT-Conference on Lasers in Manufacturing*, (2005).

[8] A.W. Snyder, J.D. Love, *Optical Waveguide Theory*, Chapman and Hall, 1983.

[9] C.L. Chen, Foundations for Guided-Wave Optics, John Wiley & Sons, 2006. http://dx.doi.org/10.1002/0470042222

[10] W. Rosenheinrich, *Tables of Some Indefinite Integrals of Bessel Functions*, University of Applied Sciences Jena, Jena, Germany, 2012.

[11] R. P. Khare, *Fiber optics and optoelectronics*, Oxford University Press, 2004.

[12] T. Saktioto, J. Ali, P.P. Yupapin, M. Fadhali, Characterization of coupling power for single-mode fiber fusion, *Optik - International Journal for Light and Electron Optics*, 121 (2010) 1802-1806. http://dx.doi.org/10.1016/j.ijleo.2009.04.019

Received: March 23, 2015; Published: June 5, 2015