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OPTICAL PROPERTIES OF 1 X 4 WEAKLY COUPLED FIBERS

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ABSTRACT
This paper shed light on the characteristics of power transfer and exchange at the coupling region of weakly coupled fiber. Fiber coupler has been fabricated by joining four identical fibers in parallel arrangement using automatic fusion and elongation technique. The fibers were heated at 1350^{o}C and gradually pulled in range of 850µm – 4500µm with pulling speed of 150µm/s and then automatically stopped when the preset coupling ratio is attained. Single power of 1 mW laser diode was launched in to one of four input ports and power released at the output ports were detected by using optical time domain and spectrum analysis. The power transfer among the fibers has been also calculated based on Coupling Mode Theory using a transfer matrix method. Our experimental and theoretical model showed a good agreement of power transfer among the fibers. By assuming that the input power is launched in to the fiber 1, this power will gradually transfer to the fiber two, fiber three and fiber four before it then turned to fiber one. We obtained the preset coupling ratio of 50%:20%:20%:10% at the coupling length of 2.5µm and the separation between fibers of 5µm. Good accuracy of the coupling ratio of the power transfer enhances the performance of the fiber coupler as passive devices and sensing application.

Keywords: Coupling length; Coupling ratio; Fiber coupler; Power transfer.

1. INTRODUCTION
The use of single mode optical fibers as passive devices and sensing tools has been greatly expanded in this decade. It was used as the optical splitter, combiner, router, and directional coupler, wavelength demultiplexing (WDM), Fiber Bragg Grating (FBG) ring resonator, and mach-zehnder interferometer. Main component to create the passive devices is fiber coupler. The fiber coupler basically consists of two input and two output ports [1-4].

Since the fiber coupler is a key element in optical communication, the need of high performance of this device such as accurate coupling ratio, coupling coefficient, low insertion and exertion loss becomes important. Many technical methods was carried out in enhancing this performance such as mechanical control of coupling ratio, the use of high temperature laser to heat coupling region, and also etching technique to obtain low coupling loss [5-12].

Fusion and elongation method are one of several techniques to fabricate fiber coupler. This method has been used by Saktioto *et al* to join two single mode fiber by heating the

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coupling region in 1000^{o}C using H_2 Gas with rate flow of 180 cc/s [12]. This research still has some limitations such as the accuracy of the coupling coefficient and coupling ratio. The speed of pulling stages was also ignored. Other interesting study in fiber coupler was also done by D. Irawan *et al* [13-15]. He studied on the optimum technique to fabricate single mode fiber coupler by using fusion technique. This study focused in to the coupling

In this research we fabricate the fiber coupler consists of four single mode fibers by using fusion and elongation technique. The fabrication process emphasizes the fiber arrangement, and the determination of power transfer between the fibers. Power characteristics will be determined based on coupling mode theory by using set of the transfer matrix. Finally, simulation and experimental results are presented to be analyzed.

2. THEORETICAL CONSIDERATION

If the amplitudes of input and output powers is denoted by $A_N(0)$ and $A_M(z)$ respectively, and by assuming that the interaction of fields only occurs between the nearest fibers only, the signal propagation is depicted in the differential equation as follows [13],

$$\frac{dA_m(z)}{dz} = -j\beta_m A_m(z) - j\kappa_{m(m-1)}A_{m-1}(z) - j\kappa_{m(m+1)}A_{m+1}(z) \qquad (1a)$$

$$\frac{dA_n(z)}{dz} = -j\beta_n A_n(z) - j\kappa_{n(n-1)}A_{n-1}(z) \qquad (1b)$$

It can be simplified as the following equation which is determined by the eigenvalue and the eigenvector that describes transformation of light intensity between the fibers as follows.

$$\begin{bmatrix} A_1(z) \\ A_2(z) \\ A_3(z) \\ . \\ . \\ . \\ A_M(Z) \end{bmatrix} = -j\left[M_{pq}\right]\begin{bmatrix} A_1(0) \\ A_2(0) \\ A_3(0) \\ . \\ . \\ . \\ A_N(0) \end{bmatrix} \qquad (2)$$

where $M_{pq} = \sum_{p,q=1}^{n} \sin\left(\frac{pm\pi}{n+1}\right)\sin\left(\frac{qm\pi}{n+1}\right)e^{\lambda_m z}$ is the transfer matrix. In this case, the power transfers among the fibers consider that the coupling coefficient is much smaller than the propagation constant. The Propagation constant is given by the following equation [14].

$$\beta = \left[\left(\frac{2\pi n_{co}}{\lambda} \right)^2 - \frac{U^2}{a^2} \right]^{1/2} \tag{3}$$

Where $\lambda_m = -2jK\cos\left(\dfrac{m}{n+1}\pi\right)$, $m, q, s, t = 1, 2, 3, ...n$ is the modes of light which represents the eigenvalue of coupled-mode differential equation, and K is the modified of Bessel function which is referred to as Hankel function. The value of $\delta = 1 - \left(n_{cl}/n_{co}\right)^2$, $V = \dfrac{2\pi a n_{cl}\sqrt{\delta}}{\lambda} = U^2 + W^2$ are defined as normalized frequency, where as $U \cong 2.405\mathrm{e}^{-\left(1-\delta/2\right)V}$ is the progression of phase, and W is the first kind of Bessel function that represents the transverse decay of amplitude.

The power exchanges among the fibers in 1X4 directional fiber coupler were also modeled based on the transfer matrix method. The transfer matrix equation for 4X4 was constructed by determining the matrix MXN given by Equation (2). It yields as follows,

$$\begin{bmatrix} A_1(z) \\ A_2(z) \\ A_3(z) \\ A_4(z) \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} A_1(0) \\ A_2(0) \\ A_3(0) \\ A_4(0) \end{bmatrix} \tag{4}$$

where

$$M_{11} = M_{44} = -\frac{\gamma_2^2(\gamma_1^2 - 1)}{\gamma}\cos(\gamma_1\kappa z) + \frac{\gamma_1^2(\gamma_2^2 - 1)}{\gamma}\cos(\gamma_2\kappa z)$$

$$M_{12} = M_{43} = -j\frac{\gamma_1(\gamma_2^2 - 1)}{\gamma}\sin(\gamma_1\kappa z) - j\frac{\gamma_2(\gamma_1^2 - 1)}{\gamma}\sin(\gamma_2\kappa z)$$

$$M_{13} = M_{42} = -\frac{1}{\gamma}\cos(\gamma_1\kappa z) + \frac{1}{\gamma}\cos(\gamma_2\kappa z)$$

$$M_{14} = M_{41} = j\frac{\gamma_1\gamma_2^2}{\gamma}\sin(\gamma_1\kappa z) - j\frac{\gamma_2\gamma_1^2}{\gamma}\sin(\gamma_2\kappa z)$$

$$M_{21} = M_{34} = j\frac{\gamma_1(\gamma_1^2 - 2)}{1}\sin(\gamma_1\kappa z) - j\frac{\gamma_2(\gamma_1^2 - 2)}{\gamma}\sin(\gamma_2\kappa z)$$

$$M_{22} = M_{33} = \frac{\gamma_1^2(\gamma_2^2 - 1)}{\gamma}\cos(\gamma_1\kappa z) - \frac{\gamma_2^2(\gamma_1^2 - 1)}{\gamma}\cos(\gamma_2\kappa z)$$

$$M_{23} = M_{32} = j\frac{\gamma_1}{\gamma}\sin(\gamma_1\kappa z) - j\frac{\gamma_2}{\gamma}\sin(\gamma_2\kappa z)$$

$$M_{24} = M_{31} = -\frac{1}{\gamma}\cos(\gamma_1\kappa z) + \frac{1}{\gamma}\cos(\gamma_2\kappa z)$$

and $\gamma = \sqrt{5}$, $\gamma_1 = \left[\frac{\sqrt{5}+3}{2}\right]^{1/2}$, and $\gamma_2 = \left[\frac{-\sqrt{5}+3}{2}\right]^{1/2}$.

3. RESULTS AND DISCUSSION

The power exchanges among four fibers of 1X4 fiber coupler were recorded while the coupling region is pulled and heated as visualized in Figure 5.4. In this case the input power was launched into the fiber 1 ($A_1(0)=1$). Before fusion process, the initial input power at fiber 1 detected by the photo detector was depicted by the red line. This power then propagates into its nearest fiber which is fiber 2 as depicted by the blue line due to the coupling coefficient between them κ_{12}. While the power at fiber 2 increased, the coupling coefficient between fiber 2 and fiber 3 κ_{23} causes this power to propagate into fiber 3 as depicted by the yellow line. It is then transferred into the fiber 4 as given by the green line due to the coupling coefficient between fiber 3 and fiber 4 κ_{34}.

The maximum values of power distribution are given by the diagonal matrix. The first row describes power at fiber 1 where M_{11} is maximum. It is then transferred to the nearest fiber which is fiber 2 as given by the second row, where M_{22} contains the maximum power. The third row describes the condition where a maximum power is at M_{33} or fiber 3. Almost of all powers is then transferred into fiber 4 as given by the fourth row of Equation (5.6) in which M_{44} has the maximum value. The modeling results of power exchange among four fiber of 1X4 directional fiber coupler using above transfer matrix is shown in Figure 5.4.

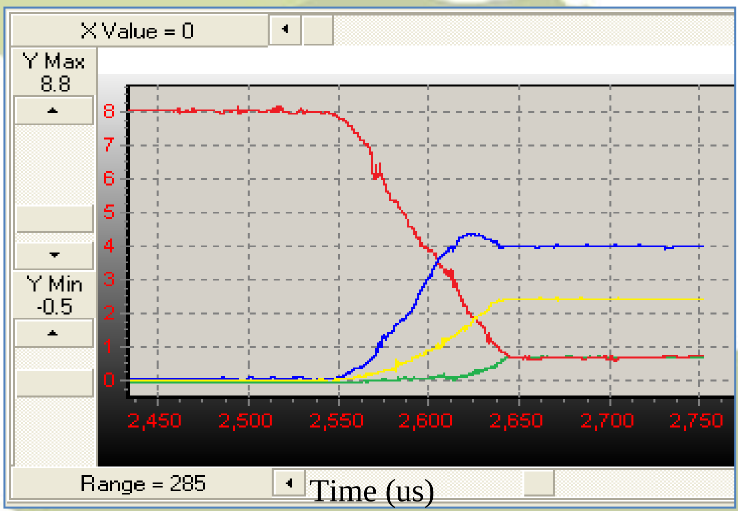

Figure 1 Experimental results of power exchanges in 1X4 fiber coupler, with input power at fiber 1 and pulling speed = 100 µm/s, EL1 = 0.341 Db

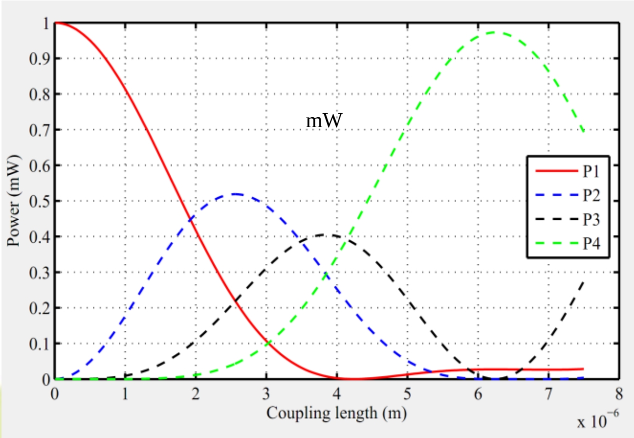

Figure 2 Theoretical result of power exchange in 1X4 fiber coupler

Good agreement between the modeling results compared to the experimental result is obtained by assuming that all fibers are in linear arrangement with identical fiber cross section, refractive index and the propagation constant. Figure 2 shows the propagation of the power transfer in fiber 1, fiber 2, fiber 3, and fiber 4. The dash-black straight line which is vertically taken at coupling length 2.5 μm shows that the pre-set coupling ratio is 50:30:10:10.

From the analysis of experimental and theoretical works of multi directional fiber couplers it is revealed that the power at initial fiber cannot be completely returned to itself after distributing its power periodically to the other fibers, or it cannot be also transferred completely to other fibers due to power loss. Unlike the fiber coupler consisting of two or three coupled fibers, optical power is able to be transferred periodically from fiber 1 to fiber 2, and to fiber 3. But this cannot be reached in the fiber coupler consisting of more than three fibers, such as 1X4. It is also due to periodical function of the coupling coefficients.

Power at fiber 3 is not only transferred to the fiber 4 due to the coupling coefficient between fiber 3 and fiber 4 κ_{34}, but it is also transferred into the fiber 2 and returned into the initial fiber 1 due to the coupling coefficient between them which are κ_{32} and κ_{21}. It can be seen clearly in Figure 2 that the maximum power transfer in fiber 4 is only about 0.8 mW, while power in fiber 1 remains increased. By increasing the coupling length subject to time of pulling length, more power is transferred to other fibers.

Power propagation in directional fiber coupler was also modeled in three dimensions. Identical output power distributions at the output ports 1X4 are shown by Figure 5.6 respectively. The power transfer and distribution are shown as function of propagation length. It also depicts that the process of power transfer in coupling region is fiber to fiber which means the initial input power is transferred into the nearest fiber before being transferred to other fibers. In this model, all fibers have identical cross section, refractive index and, propagation constant. The fibers are considered in the linear arrangement with the distance of separation between them which varies from 5 μm to 10 μm.

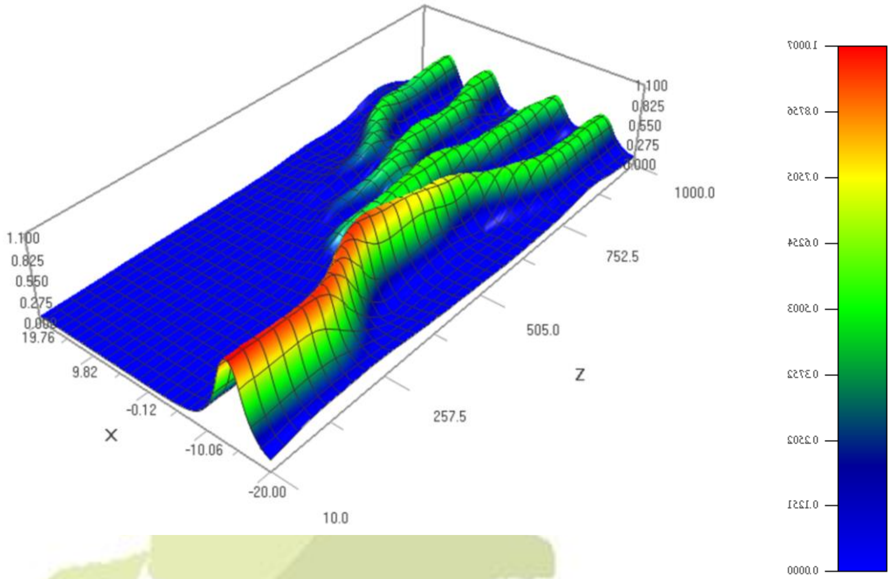

Figure 3 Power propagation along fiber coupler with separation between fiber axis d = 5 µm, a) 1X3 fiber coupler b) 1X4 fiber coupler

4. CONCLUSION

Good agreement of the experimental and theoretical results of power transfer among 1X4 weakly coupled fiber was obtained for parallel arrangement fibers which was heated at 1350^{o}C and pulled the coupling length in range of 850µm – 4500µm with elongation speed of 150µm/s. Power in initial fiber was gradually transferred into the other fibers by the coupling coefficient. Then the fix-desired coupling ratio at the output ports of 50%:20%:20%:10% was also obtained with los exertion loss of 0.341 dB.

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