Normalized Power Propagation

on 1x6 Fiber Coupler

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Abstract

The simulation of normalized power propagation on interaction region of 1x6 monolithic fiber coupler is reported. Power distribution on fiber couplers is much affected by arrangement of fibers. The theoretical model has been used to calculate power coupling propagation on linear and pentagonal arrangement of 1x6 fiber coupler. The calculation is based on a matrix transfer which is the solution of coupled-mode theory. The six parallel fiber is in linear array and pentagonal placement. By launching input power to single input of 1x6 monolithic fiber couplers for both configurations, power distribution shows how the initial power is distributed to the others. It is found that linear configuration

cannot initiate its power to the initial fiber, and maximum peak is not periodically such as power propagation on 1x2 and 1x3 fiber coupler. By changing the arrangement to be a pentagonal and one fiber as in the center where input power is launched, the input power will be distributed identically from the center to five surrounding fibers. At certain coupling length, about 4.7 mm and 6.3 mm, six fibers with pentagonal configuration will have identical output power for wavelength input 1550 and 1310 nm respectively. Based on this distribution, 1x6 monolithic fiber couplers are applicable as a power divider.

Keyword: 1x6 monolithic fiber couplers, power propagation, linear and pentagonal configurations

1 Introduction

Fiber coupler is a passive device that is important in optical network communications [1]. It fabricated by fusion technique. *N*-parallel SMF-28e®, which are electromagnetically separated and isolated, twisted together and pulled during fusion process [2-4]. The pulling process will be stopped suddenly when the desired coupling ratio is reached. But, in experiment it is difficult to be maintained [5]. So choosing better configuration is a better way to control it. Coupling ratio is a parameter that describes the output power on each output ports, and it is much affected by coupling coefficient [6]. It does not only depend on coupling coefficient, but also the configuration of the fibers. In this paper, six fibers are purposed to make a fiber coupler with single input. The propagation of coupling power is calculated based on a set of matrix transfer which is determined from coupled mode theory [7]. It is examined on linear and pentagonal configurations of 1x6 monolithic fiber couplers by launching the input power to the fiber 1 and center fiber respectively. Linear array is defined as six parallel fibers in linear arrangement, and pentagonal configuration is defined as five fibers arranged make a pentagon and added by one fiber as the center.   The calculation is based on several assumptions, where the propagation constants, separation, and cross section of the fibers are held to be constant. Another assumption is lossless fibers, which means the fiber is ideal with no loss. However, the calculation is also done to find the dependence of the wavelength and the coupling coefficient due to contribute a 1x6 monolithic fiber coupler with suitable optical device operating systems. Result of the calculation will be analyzed to determine which one the better configuration based on desired coupling ratio for many applications such as optical power divider, combiner, splitter and optical switching [8,9].

2 Theoretical Model

The propagation of light in dielectric medium was determined by Maxwell's equation. It describes how the refractive index affects the light propagating in the

waveguide. In 1983, Alan Snyder has determined the transfer of light intensities from a waveguide to others waveguides. That theory is known as coupled-mode theory and it is mathematically written as follow [10].

$$\mathbf{E}(x, y) = \sum_i a_i(z)\mathbf{E}_i(x, y)e^{-j\beta_i z} \tag{1}$$

where $\mathbf{E}(x, y, z) = \mathbf{e}_i(x, y)e^{-j\beta_1 z}$. The waveguide 1 $\mathbf{e}_1(x, y)e^{-j\beta_1 z}$ physically extend to waveguide 2 and $\mathbf{e}_2(x, y)e^{-j\beta_2 z}$ to waveguide 1. This Equation 1 describes total electric field propagating in z direction with propagation constant. Consider there are six fibers which are electromagnetically isolated apart as it can be seen in Figure 1. The cross section, propagation constants, and separation between the fibers are held to be constant.
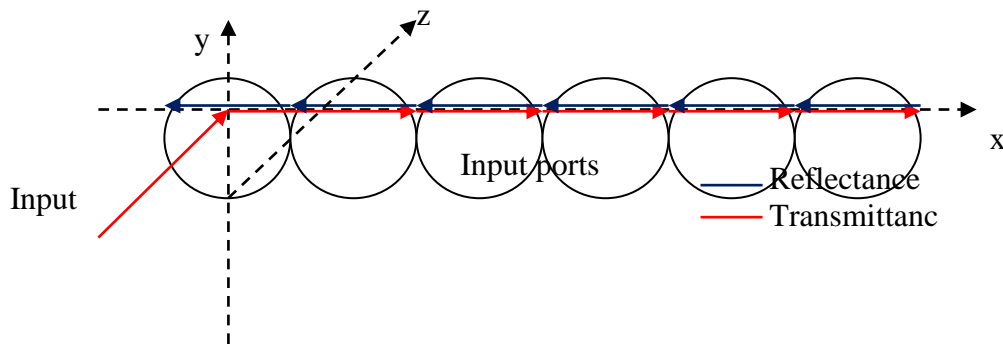

Figure 1. Illustration of light propagating on linear configuration of 1x6 monolithic fiber coupler with input power in to Input port 1.

Referring to [11, 12], the transfer power between the fibers is much depending on the coupling coefficient and propagation constants. It can be written mathematically as follow.

$$\begin{bmatrix} A_1(z) \\ A_2(z) \\ A_3(z) \\ A_4(z) \\ A_5(z) \\ A_6(z) \end{bmatrix} = \begin{bmatrix} \beta_1 & \kappa_{12} & 0 & 0 & 0 & 0 \\ \kappa_{21} & \beta_2 & \kappa_{23} & 0 & 0 & 0 \\ 0 & \kappa_{32} & \beta_3 & \kappa_{34} & 0 & 0 \\ 0 & 0 & \kappa_{43} & \beta_4 & \kappa_{45} & 0 \\ 0 & 0 & 0 & \kappa_{54} & \beta_5 & \kappa_{56} \\ 0 & 0 & 0 & 0 & \kappa_{65} & \beta_6 \end{bmatrix} \begin{bmatrix} A_1(0) \\ A_2(0) \\ A_3(0) \\ A_4(0) \\ A_5(0) \\ A_6(0) \end{bmatrix} \tag{2}$$

Equation 2 is a transfer matrix used to calculate the light transfer between the fibers. it can be seen clearly that the interaction of light occurs between the nearest fiber only. Calculating the eigenvalue and eigenvector of inner matrix in Equation 2 results power output amplitudes of each six fibers as given by equation 3. In this case the coupling coefficient is assumed much smaller than the propagation

constants, so that it called weakly coupling coefficient case. The solution of inner matrix on Equation 2 is determined by eigenvalue and eigenvector that describes transformation of light intensity between the fibers as follow.

$$
\begin{bmatrix} A_1(z) \\ A_2(z) \\ A_3(z) \\ A_4(z) \\ A_5(z) \\ A_6(z) \end{bmatrix} = -j \begin{bmatrix} M_{pq} \end{bmatrix} \begin{bmatrix} A_1(0) \\ A_2(0) \\ A_3(0) \\ A_4(0) \\ A_5(0) \\ A_6(0) \end{bmatrix}
\tag{3}
$$

Where $M_{pq} = \sum\limits_{p,q=1}^{n} \sin\left(\dfrac{pm\pi}{n+1}\right) \sin\left(\dfrac{qm\pi}{n+1}\right) e^{\lambda_m z}$ is the transfer matrix. It has been shown that the power transfers between the fibers are the case where the coupling coefficient is much smaller than the propagation constant. Propagation constant and coupling coefficient are given by Equation 4 and 5 respectively [12].

$$
\beta = \left[\left(\frac{2\pi n_1}{\lambda} \right)^2 - \frac{U^2}{\rho^2} \right]^{1/2}
\tag{4}
$$

$$
\kappa = \frac{\sqrt{\delta} U^2 K_0 \left[W(d/\rho) \right]}{\rho V^3 K_1^2(W)}
\tag{5}
$$

where λ is the wavelength of light in vacuum, K 's are modified Hankel function, $\delta = 1 - \left(\dfrac{n_2}{n_1} \right)^2$, $V = \dfrac{2\pi \rho n_1 \sqrt{\delta}}{\lambda} = U^2 + W^2$ is a normalized frequency, and $U \cong 2.405 e^{-\left(1 - \delta/2\right)V}$ is the progression of phase, and W is the transverse decay of amplitude.

The solution of Equation 3 consists of coupling coefficient and propagation constant. Assuming the cross section, separation of the fibers, and propagation constant held to be constant, the light intensity P_N in each output ports can be written as follows.

$$
P_N(z) = \left[A_N(z) \right]^2 =
$$
$$
\sum\limits_{m=1}^{n} \sum\limits_{q=1}^{n} \sum\limits_{s=1}^{n} \sum\limits_{t=1}^{n} \sin\left(\frac{is\pi}{n+1} \right) \sin\left(\frac{ms\pi}{n+1} \right) \sin\left(\frac{it\pi}{n+1} \right) \sin\left(\frac{qt\pi}{n+1} \right)
\tag{6}
$$
$$
e^{(\lambda_s + \lambda_c)z} \sqrt{P_q(0) P_m(0)}
$$

Where $\lambda_m = -2jK\cos\left(\dfrac{m}{n+1}\pi\right)$, $m,q,s,t = 1,2,3,...6$ are eigenvalues of coupled-mode differential matrix.

For the second configuration the six fibers are not in linear array, but it make a pentagonal arrangement with a fiber as a center and surrounded by fiber other fibers as shown by Figure 2. The propagation constant of six fibers are held to be constant. The coupling coefficient and cross section of five surrounding fibers are identical but it is different with the center. In this case the cross section of center fiber is smaller than outer due to fix a pentagonal configuration.
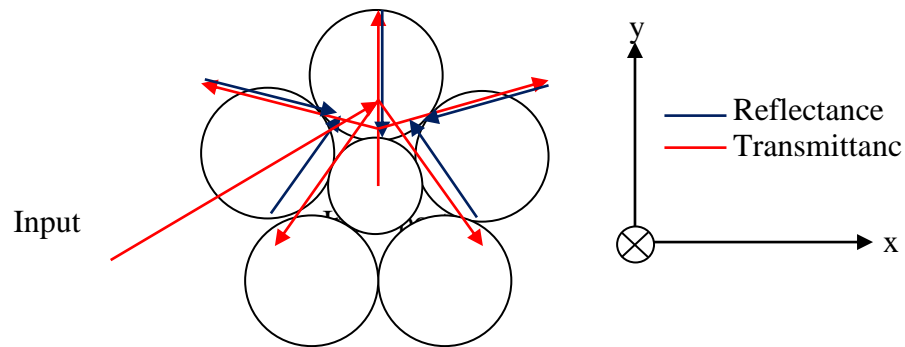

Figure 2. Pentagonal configuration of 1x6 Fiber coupler

The fixed pentagonal configuration with a fiber as a center is twisted together before fusion process. Where L is denoted as length of the interaction region. By launching the light intensity to the center of pentagonal configurations such as monolithic 1x6 fiber coupler, the power in the center P_0 will be distributed to the five surrounding fibers P_N.

3 Results and Discussion

The calculation of coupling power propagation on 1x6 monolithic fiber couplers has been shown that the transfer power between them does not only depend on the coupling coefficient of each fiber, but also the arrangement of that six fibers. Launching 1 mW CW Laser as input power to the fiber 1 in linear arrangement given by Figure 1, the coupling power propagation versus phase is shown by Figure 3. It describes that power in fiber 1 is transferred respectively to the fiber 2, fiber 3, fiber 4, fiber 5 and and finally fiber 6. After coupling and oscillation, power will drop and then increase until reaches the secondary peaks. The maximum power in fiber 6 could not be equal to 1mW and also does not occur periodically such as coupling power propagation in 1x2 and 1x3 fiber couplers

that have been reported [9].   To control the coupling ratio of this linear 1x6 fiber coupler, coupling coefficient is possible to be adjusted. It is done by adjusting the separation and the refractive index of the fibers. In experiment It is not too easy, because the fusion process sometimes changes the geometry of the fibers. Another way to control the coupling ratio is adjusting the length of interaction region. Again, it is also not easy, because when the pulling in fusion process is stopped suddenly, the interaction region will still elongate in nanometer scale. Certainly its change caused the desired output power characteristic
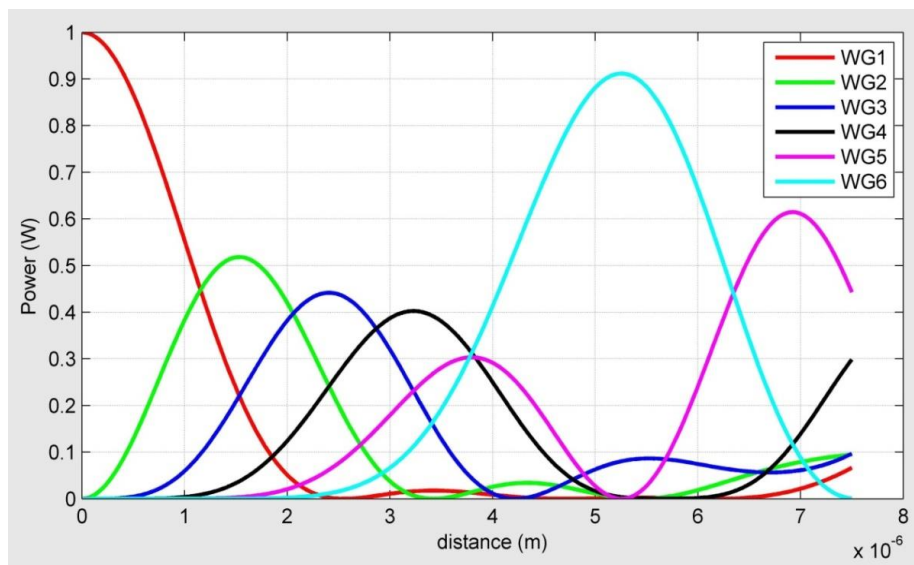

Figure 3. Coupling power propagation of linear configuration 1x6 monolithic fiber coupler by launching input power to the end of fiber (fiber 1 or fiber 6)

The calculation of coupling power propagation on pentagonal configuration 1x6 monolithic fiber coupler given by Figure 2 has shown a good agreement between the coupling power and the length of the interaction region. It can be seen in Figure 4 that the coupling power propagates periodically. When 1mW Laser with wavelength 1550 nm as Input power launched to the center fiber, It will be distributed equally to the five surrounding fibers. Distance in millimeter denotes length of interaction region. It can be seen clearly that at certain distance i.e. 4.7 mm, and 14.3 mm, the 1x6 monolithic fiber couplers has identical output power in six output ports.
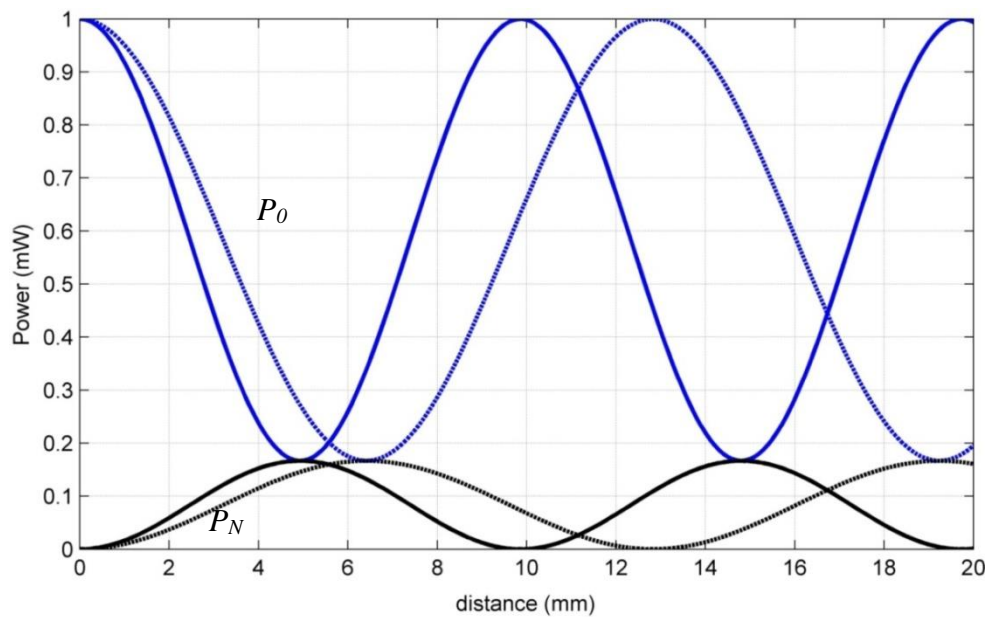
Figure 4. Coupling power propagation on pentagonal configuration with power input launched to the center fibers.

The dash line in Figure 4 denotes the calculation of coupling power propagation on the same pentagonal configuration of 1x6 monolithic fiber coupler, but the wavelength of Laser input is 1310 nm. It shows that the coupling length using power with wavelength 1550 nm is shorter than using 1310 nm. it caused by proportionality coupling coefficient and wavelength as given by Equation 5. The higher wavelength, the higher coupling coefficient is, and the shorter length of the interaction region needed to make a pentagonal 1x6 fiber coupler has equal output power. Based on this equality, pentagonal configuration promises 1x6 fiber couplers as a good power divider, power combiner and optical switch.

4. Conclusion

The coupling power propagation of 1x6 monolithic fiber couplers has been investigated both linear and pentagonal configurations. It has shown that the coupling coefficient is an important parameter that can be adjusted due to get desired coupling ratio. Coupling power propagation on linear configuration has shown that the 1x6 fiber coupler could not transfer totally its initial power to fiber 6. The fiber 6 has the slowest coupling velocity that others fiver fiber. It is found that the coupling ratio is difficult to be controlled than coupling ration in pentagonal configuration. Where the input power not only be able to be distributed identically to the five surrounding fibers, but also the six fibers be able to have identical output power at certain distance. The calculation of coupling power on pentagonal configuration shows how the distance of propagation affected

by changing the wavelength operation. The longer wavelength the shorter length of interaction region needed to make equal output power in six output ports. Although, the 1x6 fiber coupler is a optical devices that is applicable as Optical power splitter, combiner, divider, and optical switch.

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