

Estimation of coupling coefficient and refractive index for fused coupled fibers

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ABSTRACT

Fiber couplers are widely used in telecommunication and industry as a passive splitting power device. The effective power coupling and transmitting from one fiber to another is mainly determined by both coupling length and coupling coefficient. Coupling length can be calculated directly but for coupling coefficient it depends upon the refractive index and separation fiber axis. After fusion processes of two SMF-28e[®] couplers, the refractive index is unknown due to change in the radius of fiber ($r_{\text{cladd}} < 40\mu\text{m}$ and $r_{\text{core}} < 1.5\mu\text{m}$). Coupling coefficient range is obtained from a distribution of coupling ratio and compared with the empirical formula which also enables to calculate refractive index. In this experiment, coupling coefficient in the range of 0.6-0.9/mm is calculated as a function of separation fiber axis and refractive index of core and cladding. The result shows a good correlation between experimental results and theoretical calculation.

Keywords: single mode fiber, coupling ratio, coupling length, coupling coefficient, refractive index

1. INTRODUCTION

Single Mode Fiber (SMF) directional couplers made by fusion elongation method have stimulated considerable interest in a variety of scientific fields over the last few years. Because of their promising potential for high-capacity data processing, single mode fibers are finding more usage as transmission system ¹. Their unique properties also make them particularly interesting for a broad range of applications.

Fiber coupler produces coupling coefficient that controls the effective power transmission to another junctions. Even though modeling of fiber coupling provide good understanding of the coupling coefficient, but experimentally the determination of the coupling range is not clearly established. Various approaches has been investigated ^{2,3} on the fabrication of fiber-to-fiber couplers. However, there are not many publications on coupling coefficient range corresponding to refractive index of fibers couplers.

We report in this paper the results of a theoretical and experimental analysis of single mode fiber couplers. Experimental measurements are presented in order to better describe the behavior and operation of fiber couplers as a fiber optic system. The results of a weak-coupling theoretical approach are reported and found to predict rather well with the observed geometrical parameters of the coupler properties, coupling coefficient and refractive index. The refractive index is found to decrease after fusion ⁴. The dependence of the coupling coefficient on separation fiber axis and refractive index are also discussed.

2. COUPLED FIBER AND COUPLING COEFFICIENT

Photonic circuits for various applications can be realized if the required functional devices in integrated optics form are well understood. A passive device is one in which there is no control over phenomena due to a wide range of parameter changes occurring the same time during fusion such as optical couplers. One important phenomena occurring to optical couplers, as coupling of mode in space ^{5,6,7} which contributes power propagation along coupled fiber is the coupling coefficient. Even though the determination of coupling coefficient for a practical directional coupler is difficult, however; by evaluating the channel waveguide modes and observing the fiber geometry, some calculation of coupling coefficient range can be obtained.

Consider a coupled fiber splitting one source to become two transmissions as Y junction. Two identical single mode coupled fiber; 1X2 coupler ⁸ for power propagation at z axial length can be described as,

$$\left. \begin{aligned} P_2 &= P_o \sin^2(\kappa z) \\ P_1 &= P_o - P_2 = P_o[1 - \sin^2(\kappa z)] = P_o \cos^2(\kappa z) \end{aligned} \right\} \quad (1)$$

where the power is split to fiber 1 and fiber 2. Axial length is periodically changed by $z = m\pi/\kappa$; $m=0,1,2,\dots$, for $m=1$, $z=L_c = \pi/\kappa$.

L_c is the coupling length in millimeter unit. $P_2/(P_1+P_2)$ and $P_1/(P_1+P_2)$ are respectively defined as coupling power and transmission power. Both the power fraction is called coupling ratio. A laser diode source of wavelength $\lambda = 1310\text{nm}$ is used and is related to the normalized frequency as

$$V = 2\pi a / [\lambda (n_1^2 - n_2^2)^{1/2}] \quad (2)$$

To show the wave propagation along two close fibers, coupled modes equation simply can be taken ^[5] as

$$\left. \begin{aligned} U_1(z) &= A(z) \exp(-i\beta_1 z) \\ U_2(z) &= A(z) \exp(-i\beta_2 z) \end{aligned} \right\} \quad (3)$$

Derivation of coupled mode equations for two waveguide system is as follows:

$$\left. \begin{aligned} dU_1/dz &= -i\beta_1 U_1 - iK_{12}U_2 \\ dU_2/dz &= -i\beta_2 U_2 - iK_{21}U_1 \end{aligned} \right\} \quad (4)$$

The first term on the right hand side of equation (4) is the usual propagation term and the second one refers to the coupling term. This equation propagates as a sine and cosine wave. Therefore, coupled mode solutions are:

$$\left. \begin{aligned} U_2(z) &= \kappa / \sqrt{(\kappa^2 + \delta^2)} \sin(\kappa z) \\ U_1(z) &= \sqrt{1 - U_2^2(z)} \end{aligned} \right\} \quad (5)$$

where $\kappa = \sqrt{(\delta^2 + K_{12}K_{21})}$ is coupling coefficient and δ which is the phase mismatch factor is defined as $(\beta_1 - \beta_2)/2$. Then coupling coefficient ^[9] can be defined as following

$$\kappa = \frac{(2\Delta)^{1/2}}{a} \frac{u^2}{V^3} \frac{K_o(wd/a)}{K_1^2(w)} \quad (6)$$

where K_o and K_1 are zeroth and first order of Hankel function, u and w are respectively normalized lateral phase constant and normalized lateral attenuation constant. The symbol of Δ is defined by $(n_1^2 - n_2^2)/2n_1^2$, a is the core radius and d is the separation fiber axis between cores.

At the same range position, κ can also be expressed as an effective power range for transmission to another fiber. The separation between two fibers is significant in coupling coefficient, because it determines the effective power transmission to another fiber. To solve coupling coefficient, a simple empirical relationship is used to calculate the value κ ⁸ which is as follows:

$$\kappa = (\pi/2) (\sqrt{\delta/a}) \exp [-(A + B \bar{d} + C \bar{d}^2)] \tag{7}$$

where $A = 5.2789 - 3.663V + 0.3841V^2$
 $B = -7769 + 1.2252V - 0.012V^2$
 $C = -0.0175 - 0.0064V - 0.0009V^2$
 $\delta = (n_1^2 - n_2^2)/n_1^2$; $\bar{d} = d/a$

n_1 and n_2 are respectively core and cladding refractive index.

3. EXPERIMENTAL DESIGN AND OPERATION

Figure 1 depicts the schematic of SMF-28e[®] coupler fusion process. Two fibers are twisted once to have a tightly coupling when pulled by a vacuum pump and heated by H₂ gas flame torch at 1 bar. Two fibers are heated in the range of 800-1300°C, while the vacuum pump pulls the fibers to the left and right side at speed of 100µm/s approximately. The operation of the coupler machine is to reach a certain coupling ratio by fusion of fibers. The coupling ratio is detected by InGaS photo detector as shown on the monitor. Fusion fibers at the coupling region decreases from 75% until 85% in geometry size where the previous core and cladding diameter are respectively 8.2µm and 125µm.

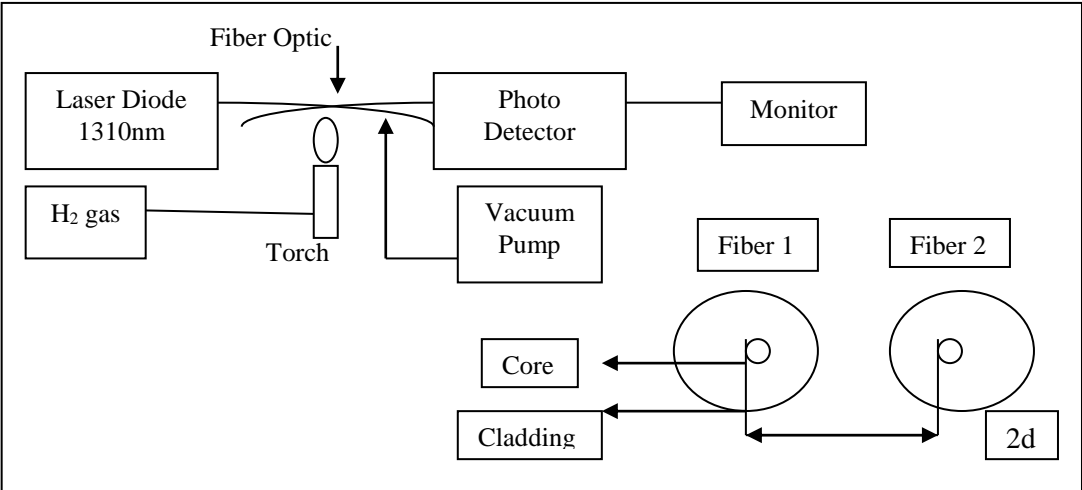


Figure 1. The schematic of SMF-28e coupler fusion process

4. RESULTS AND DISCUSSION

In fusion process, heating coupled fibers are not homogenous in changing their structures and geometries at coupling region. Their changes are complicated because refractive indices and fiber geometries are not linear. However, they tend to decrease exponentially along fibers from one edge to the center of coupling region and again increase to one end. It also occurs to wave and power propagation along the coupling region. For simplicity, these results only concentrate at the center of coupling region with a homogeneous structure and geometry.

Measurements of fused coupling fibers geometry are observed by a microscope. Using equation (1) coupling length can be determined as shown in Figure 2. Coupling ratio of x and $(100-x)$ is the ratio of transmission and coupling power. In this calculation, κ is fixed at 0.903, core and cladding refractive index as $n_1= 1.4677$, $n_2=1.4626$, and the core radius $a=4.1\mu\text{m}$. Figure 3 shows the coupling coefficient of SMF-28e[®] versus coupling ratio. Theoretical and experimental results agree that coupling length increases over coupling ratio due to the power propagation at coupling region. It takes a longer time to reach complete coupling power where the time is proportional to coupling ratio.

Coupling length through measurement and fixed κ differ over a range of 0.25mm. This is due to the separation of fibers, d which cannot be precisely measured. For the calculation purpose the value is set at $10\mu\text{m}$. Power loss during fusion also contributes to the coupling ratio range, however; for the calculation of fixed κ it is not considered. Obtaining good coupling ratio, the experimental result meets the power transmission at coupling region with larger coupling length than calculation result. However, the coupling coefficient obtained from Figure 3 is not constant. In range of 0.6-0.9/mm the coupling coefficient exists along the coupling ratio increases. This can be explained by assuming that the power transmission and coupling occurs during fusion and fluctuates some parameters such as fibers twisting, fibers heating, and refractive index changes which cannot be controlled experimentally.

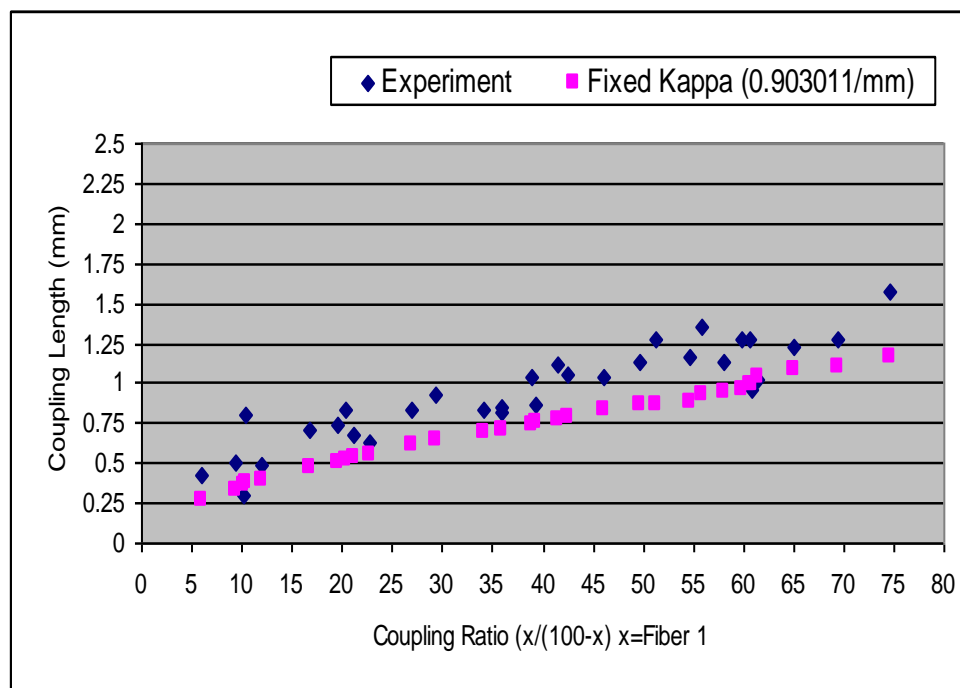


Figure 2. Comparison of Coupling Length of SMF 28e[®]

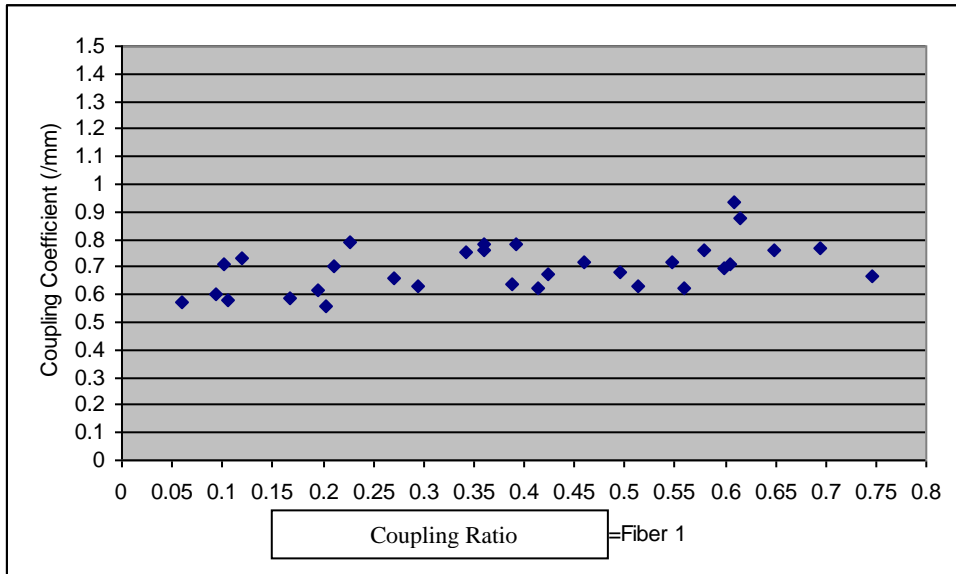


Figure 3. Coupling Coefficient of SMF coupler

To analyze the coupling coefficient dependence towards refractive index, Figure 4 describes two graphs of refractive index of fibers before and after fusion. Before fusion, refractive index is higher than that of after fusion. At the end of fusion process the coupling ratio together with refractive index of core and cladding changes.

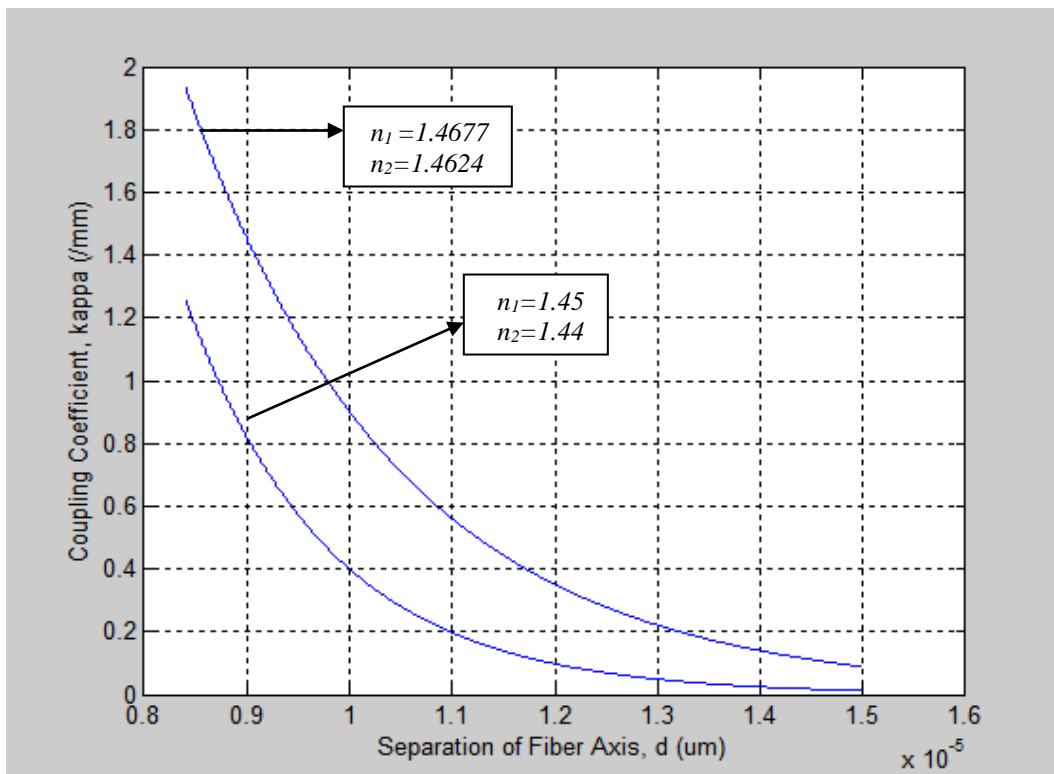


Figure 4. Coupling Coefficient of SMF-28e coupler heated by torch flame.

Two graphs also represent a boundary of fiber refractive index occurs when the fibers are fused at $n_1=1.45$ and $n_2=1.44$. It is expected that κ is in the range of between two refractive index boundaries following Equation (7). However, in Figure 3 the coupling coefficient can be obtained by a separation fiber axis and κ is in the range of 0.6-0.9/mm. This corresponds to the axial separation fiber of 10-10.86 μm at $n_1=1.4677$ and $n_2=1.4624$. Comparing the cladding diameter experimentally obtained in the range of coupling ratio of 1 to 75, where $2d = 18\text{-}35\mu\text{m}$, it is found that the separation between the two cores is $d= 9$ to $17.5\mu\text{m}$.

In order to ensure that the refractive index after fusion is a boundary range, given the mean separation of fibers $d=10\text{-}10.86\mu\text{m}$. Figure 5 shows that δ decreases rapidly from 0.007-0.001 with a high gradient until coupling coefficient approximately reaches 0.3. This explains why the refractive index will not attain $n_1=1.45$ and $n_2=1.44$ when fibers are fused since the power transmission keep flowing along the fibers is high. Hence, in Figure 4 the value of κ can agree with the requirement of boundary conditions. By setting $\kappa = 0.9\text{-}0.6/\text{mm}$, the refractive index change $(n_1^2-n_2^2)/n_1^2$ is in the range of 0.0086-0.092. Implicitly, this number is δ where the refractive index of both core and cladding after fusion. Analytical evaluation gives δ , n_2/n_1 is in between 0.9956-0.9953. This is assumed that the ratio n_2/n_1 will proportionally decreases with κ . Thus typically it is found that $n_2=1.4577\text{-}1.4556$ and $n_1=1.4640\text{-}1.4623$. Again, these values are within the coupling ratio of 1-75% of coupled fibers.

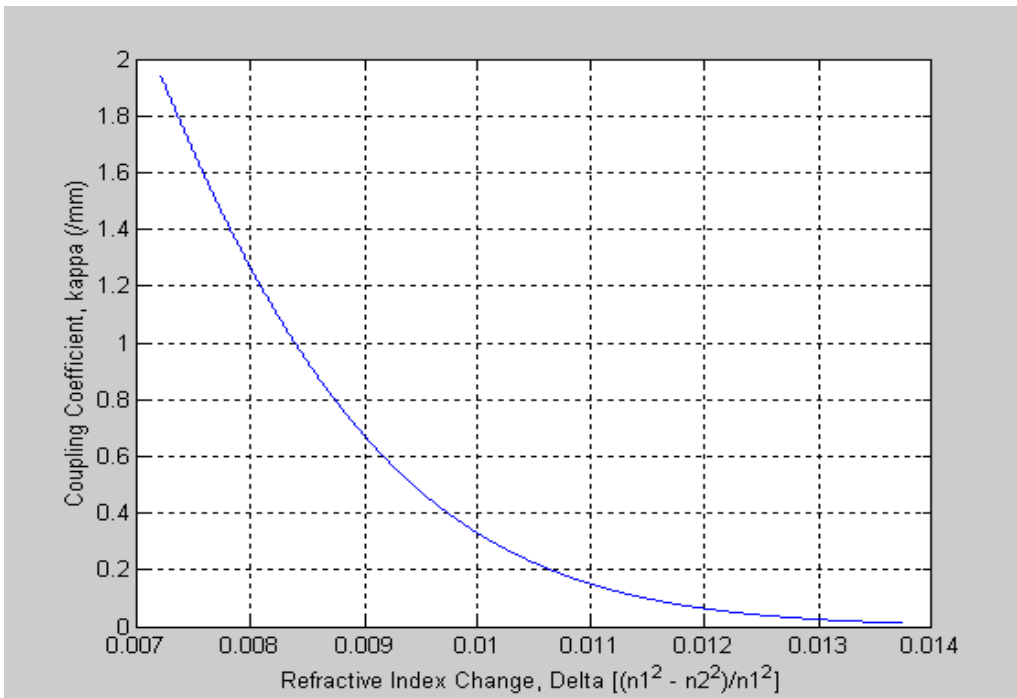


Figure 5. Refractive index decreases due to fused fibers for $n_1=1.4677\text{-}1.45$, $n_2=1.4624\text{-}1.44$

A gradient result 0.9956 and 0.9953 in Figure 6 represents the relation of refractive index with coupling coefficient at 0.9-0.6/mm. The slit range shown is narrow compared to small changes of refractive index by a factor 10^{-3} . The value of κ extends widely as expected from equation (6) and (7). The upper ends of two lines are the initial of n_1 and n_2 then decreases. The decreasing change of refractive index from initial point to the last together with $\Delta\kappa$ is in 0.24-0.36% for core and 0.31-0.45% for cladding. Coupling coefficient depends upon the refractive index, but it is not *vice versa*.

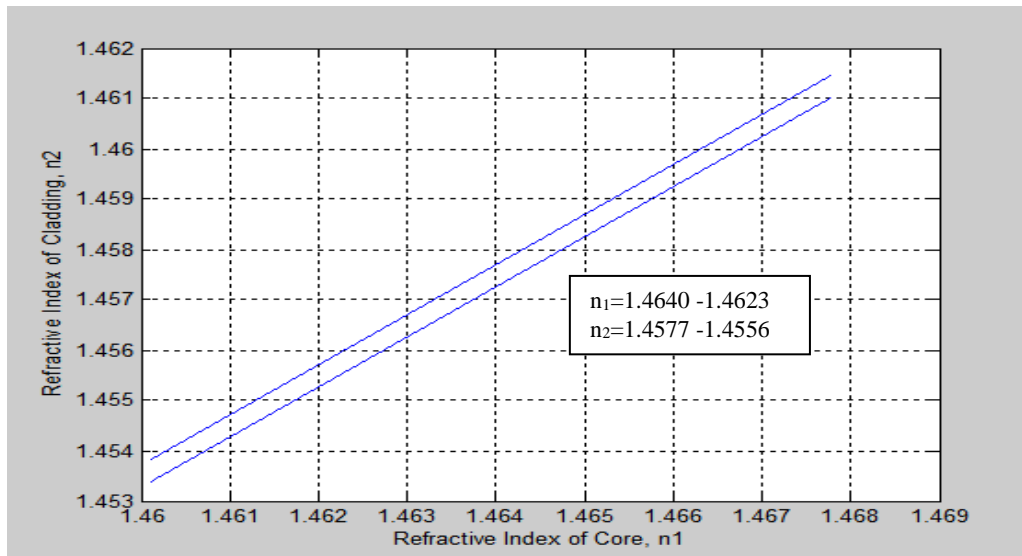


Figure 6. Gradient of refractive index for kappa 0.9/mm (upper line) and 0.6/mm

Comparing Figure 4 and 5, coupling coefficient is mainly affected by fiber separation by a factor 10^{-1} rather than the refractive index which is by a factor 10^{-2} . Decreasing of refractive index reduces wave propagation along fibers in time and position and the mode will widely travel to both claddings, whereas decreasing of core fiber separation affects that the coupling ratio can be attained earlier and this effective power can be split readily to Y junction.

According to equation (7), the value of κ depends on d by exponential factor and δ rather than refractive index of n_1 and n_2 . V and a are assumed constant. These parameters actually vary during the process together with a wave number and propagation constant due to changes of fiber geometry. This description can be observed in Figure 7. Since d is proportional to κ , then increasing d at fixed δ will increase κ , although separation of fibers is in a wide range. For a given core spacing, the coupling strength increases with the wavelength. This is due the fact that the field extends deeper into the cladding and typical values are in the range of 0.1 to 2 mm^{-1} for core spacing in the range of 4 to $15 \mu\text{m}$. It also shows a strong decrease when the fiber core spacing increases, as expected from equation (6) by assuming that interaction length is not considered to the radius of the curvature of the fibers and the wavelength. On the other hand, δ rapidly change at higher d value rather than at lower d . Refractive index difference between core and cladding is important because it dictates power coupling and transmission as the coupling coefficient is increased. However, if it occurs the power and wave will radiate extensively into cladding within a wider range. On the contrary this is not the case for a single mode fiber. Therefore it is necessary to obtain higher coupling coefficient where both d and δ are optimized, although both parameters cannot be controlled easily during fusion process since fibers are heated along the time until coupling ratio pre-set is reached.

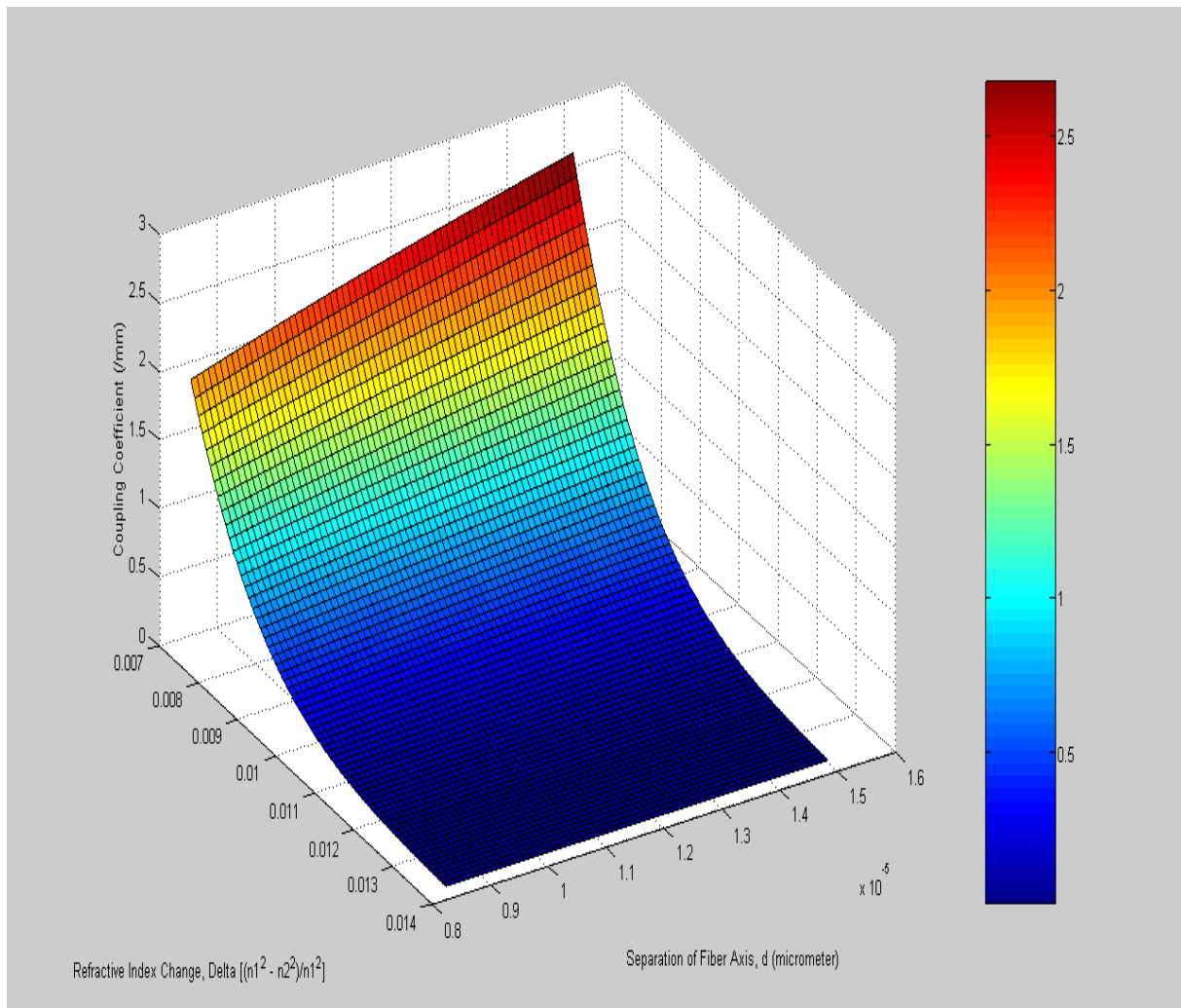


Figure 7. Coupling Coefficient of SMF-28e for wide range of δ and d . $n_1=1.4677-1.45$, and $n_2=1.4624-1.44$

5. CONCLUSION

Coupling coefficient based on distribution of coupling ratio has been obtained. It is in the range of 0.9-0.6/mm corresponding to determination of refractive index by the empirical equation to core and cladding respectively as $n_1=1.4640-1.4623$ and $n_2=1.4577-1.4556$. The experimental results obtained are in good agreement with the empirical equation and also good correlation with the theory.

ACKNOWLEDMENT

We would like to thank the Government of Malaysia, Universiti Teknologi Malaysia, and University of Riau, Indonesia for their generous support in this research.

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