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Design and Simulation of a Low Loss Optical Fiber Coupler

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Abstract

We report on the design and simulation of a compact and low loss single mode fiber matched 2x2 optical coupler. The design utilizes the evanescent field coupling mechanism. The MATLAB software has been used to simulate the design. The simulation shows that the designed 50:50 coupler exhibit low insertion losses of 3.01 dB and low excess losses of 0.13 dB which is less than the presently available coupler. The length of our designed coupler is also smaller compared with the presently available coupler. Preliminary simulated results show promising characteristics.

Keywords: Optical fiber coupler, coupling length, coupling ratio, core spacing, radius of curvature, MATLAB.

Introduction

The ability of an optical fiber coupler to transfer light from one fiber to another makes it one of the key components of an optical fiber system. In addition, it also serves to increase the umber of terminal connections permissible within the development of optical fiber communication networks. Fiber coupling with losses remains an important aspect of optical fiber communication system.

Optical interconnects are therefore one of the basic elements of optical fiber networks. Ideal fiber couplers should distribute light among the branches fibers with no loss and they should function with complete insensitivity to factors including the distribution of light between the fiber modes as well as the state of polarization of light. Unfortunately in practice passive fiber couplers do not display all of the above properties and hence the characteristics of the device affect the performance of optical fiber network. Hence coupler in a network cannot usually be treated as individual components with known parameters, a factor which necessitates certain compromises in their application

Present Scenario of Optical Coupler

At present the losses in optical couplers can be reduced to a negligible value. The characteristics of a typical coupler are shown in Table 1.1

Table 1.1 specifications of single mode couplers [1(2) x 2] [1]

Parameter		Specification	
Operation wavelength (mm)		1310 & 1550 $\pm$ 40	
Port configuration		1 x 2 or 2 x 2	
Coupling ratio (%)		1 : 99 to 50 : 50	
Grade		Supreme	High
	50 / 50	3.6 / 3.6	3.9 / 3.9
	45 / 55	4.2 / 3.3	4.4 / 3.5
	40 / 60	4.7 / 2.8	5.0 /2.9
	35 / 65	5.4 / 2.4	5.6 / 2.5
	33 / 67	5.6 / 2.2	5.9 / 2.3
	30 / 60	6.0 / 2.0	6.4 / 2.1
	25 / 75	7.1 / 1.7	7.4 / 1.8
	20 / 80	7.9 / 1.3	8.5 / 1.4
	15 / 85	9.8 / 1.0	10.4 / 1.1
	10 / 90	11.3 / 0.7	12.7 / 0.8
	5 /95	15.1 / 0.4	16.2 / 0.5
	1 /99	23.5 / 0.35	24.0 /0.4
Excess loss (dB, Typ.)		0.1	
PDL (dB, Typ.)		0.15	0.2

From Table 1.1 we see that, considerable figure of losses are present in a typical optical coupler. So our goal is to reduce the losses and improve the performance of a coupler.

Early optical fibers had attenuation of many hundreds of db/km. In modern fibers this has been reduced to 0.2dB/km at a wavelength of 1550 nm. In parallel with the development of fiber wave guide, attention was focused on the other optical components, which would constitute the optical fiber communication system. Hence, the fiber based optical couplers losses should be near about 0.2 dB/ km.

It is apparent that fiber coupling with losses remains important aspect of optical fiber communication system

Theorotical Considerations for the Design of Optical Coupler

Coupler types and technologies:

Couplers have several distinct types technology based device to meet performance requirements. The power transfer takes place in optical coupler either:

a. through the fiber core cross section by butt joining the fibers or by using some form of imaging optics between the fibers (core interaction type); or
b. through the fiber surface and normal to its axis by converting the guided core modes to both cladding and refracted modes which then enable the power sharing mechanism (surface interaction types).

Multi Port Coupler

Couplers are configured differently with the following four main categories [2]:

- T and Y couplers are the three port-port devices that split one input between two outputs.
- Tree or 1-to-n couplers take a signal input and split it among multiple outputs.
- Star couplers, a central mixing element with fibers radiating with outward like star.
- Wavelength-selective couplers, distribute signal according to their wavelengths.

We have selected Y-coupler for our design because it is extremely efficient and easy at splitting ratio and moreover, Y-coupler is versatile.

Optical Fiber Coupling Losses

Ideally, optical signals coupled between fiber optic components are transmitted with no loss of light. However there is always some type of imperfection present at optical coupler that causes losses of light. We have considered Insertion loss, absorption loss, scattering loss, bending loss, Excess loss. The following loss formulae have been considered to find out the losses in a coupler.

Insertion Loss (IL): The loss of coupler is the ratio of output to input light power at particular wavelength [3].

$$\text{Insertion loss at port 1, IL1} = 10\log_{10}(Po/P1) \quad (1)$$

$$\text{Insertion loss at port 2, IL2} = 10\log_{10}(Po/P2) \quad (2)$$

Where

Po is the power launched in core at Z=0,

$P1 = Po\{\cos(CZ)\}^2$ is the power at port 1 and

$P2 = Po\{\sin(CZ)\}^2$ is the power at port 2. C is the coupling co-efficient and Z is the total length.

Excess Loss (Pex): Ideally the sum of all output power should be equal to the input power. Excess loss quantifies the deviation from this ideal state. It can be calculated as [4].

$$Pex(dB) = -10\log[(P1+P2)/Po] \quad (3)$$

Where Po, P1and P2 are defined parameters.

Bending Loss(Ls: Radiation loss occurs when a single mode fiber is bend. Accurate modeling of this bend loss is essential for the design of optical coupler [5].

$$Ls = 8.686 \text{ x } \alpha Lb \tag{4}$$

Where
$\alpha = 65469\exp(-985.57R)$ [5];
$Lb = 2\,\Theta\,(R)$
$\Theta = \arccos(x)$
$x = (R-O)/R$

R is the selected radius of curvature and O is the offset.
Ls is the bending loss, Lb is the total length of bend fiber.

Scattering Loss (Ls): Scattering losses are caused by the imperfections in the core material and irregularities between the junctions. For a single component glass the Rayleigh scattering formula are given as [4].

$$Ls = 10\log(1/Lf) \tag{5}$$

Where

Lf is the loss factor written as

$Lf = \exp(-\gamma L1)$;

$\gamma = 1.895\text{x}10^{-28}/\lambda^4 \text{ m}^{-4}$
L1 is the total length and λ is the wavelength.

Absorption loss (La): Absorption loss is caused by the presence of impurities such as traces of metal ions and hydroxyl ions [3].

$$\text{Absorption loss } La = .001 \text{ x } L1 \tag{6}$$

L1 is the total length of the coupler.

Coupler Design

Manufacturing of Optical Coupler: There are several types of couplers implementing etching, polishing and fusing techniques to manufacture them. Among different manufacturing techniques, etched and polished couplers [6], involve time consuming manufacturing process, the fusion technique is easily automated resulting in couplers that are symmetrical, exhibit high directionality, low loss and relatively stable [4] [8] [9].

Modeling of Optical Coupler: We have used the evanescent field coupling mechanism in our optical coupler design [10].

Coupling Formulas: The power distribution after a distance Z inside a lossless coupler consisting of two parallel fibers is given by [8]

$$P_1 = Po\cos^2(CZ) \quad (7)$$

$$P_2 = Po\sin^2(CZ) \quad (8)$$

Where Po is the power launched in core 1 at Z=0, and C is the coupling coefficient or the two coupled modes under consideration and the coupling length.

$$Lc = \pi/2C \quad (9)$$

An approximate analytical expression for the coupling coefficient C is given by [11]

$$[C] = \frac{2\pi}{\lambda\alpha^2}\sqrt{(1-\frac{n^2{}_{cl}}{n^2{}_{co}})}\,\frac{n^2{}_{co}-n^2{}_{eff}}{n^2{}_{co}-n^2{}_{cl}}\,\frac{K_0[x]}{K^2{}_1[y]} \quad (10)$$

Where

$n_{eff} = (n_{co} + n_{cl})/2$

$x = 2(\alpha + \Delta)*(n_{eff}{}^2 - n_{cl}{}^2)^{1/2}$

$y = \alpha\,(n_{eff}{}^2 - n_{cl}{}^2)^{1/2}$

$\alpha = 2\pi a/\lambda$

$\Delta = \pi d/\lambda$

With d being the spacing between the fiber core boundaries and Kv the modified Bessel functions of the second kind of order v.

The power-coupling ratio can be described as [12] [13]:

$$\eta = \sin^2[\pi/2*\{(L/Lc) + (Lend / Lc)\}] \quad (11)$$

Where L is the length of the straight section, Lend is the increase in coupling length, and Lc is the total coupling length.

$$\text{Angle, } \theta = \arccos\{(R - O) / R\} \quad (12)$$

The offset O can be calculated

$$O = (D - d)/2 \quad (13)$$

Where D is the diameter of the cladding, d is the distance between two core boundaries of the fiber and R is he radius of curvature.

The bending length is given by

$$Lb = 2 \text{ x } \theta \text{ x } R \quad (14)$$

Therefore total coupler length becomes

$$Lt = 2xLb+L \quad (15)$$

Design Layout of Optical Coupler

The physical dimension of the couplers is summed up in fig 1.

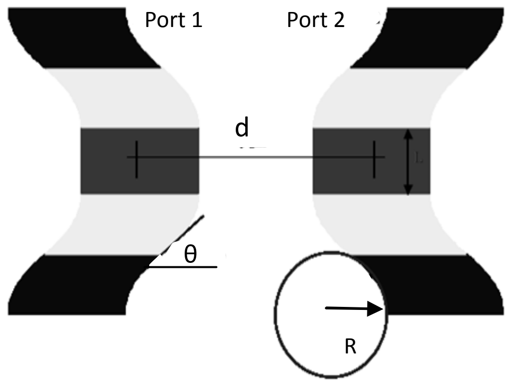

Figure 1: Physical layout of designed coupler.

The physical layout of the designed coupler shown in figure consists of three regions, the middle region is the coupling length and the other two region forms S-bend region.

To create the necessary separation between the fibers the bending technology has been used. In our design we have used cosine type S-bend. The bending has been created in both side of the straight portion of the fibers. The straight portion is the coupling region. Only the cladding of this straight portion has been partially removed.*5)*

Fabrication of the Coupler

Micro Structured Polymer Optical Fiber (MPOF) technique [14] was selected to fabricate the coupler. Unlike silica fibers [15], which are generally fabricated by stacking an array of silica capillaries and rods, MPOF performs, can be made by a variety of techniques. It helps to reduce the core spacing to our desired value.

Simulation and Result

The parameters of the optical fiber that has been selected for our coupler design are [15]:

- Core diameter = 8 μm
- Cladding diameter = 125 μm
- Core refractive index = 1.5
- Normalized frequency = 3.9585
- Cladding refractive index = 1.48
- Cut off wavelength = 1.7008 μm
- Critical radius = 0.0018 m

These are the values that are used in presently available coupler. We will change only the value of core spacing and radius of curvature.

The equations 9 ~11 were simulated using MATLAB.

The simulated result for d = 4.08 µm is shown in fig. 2

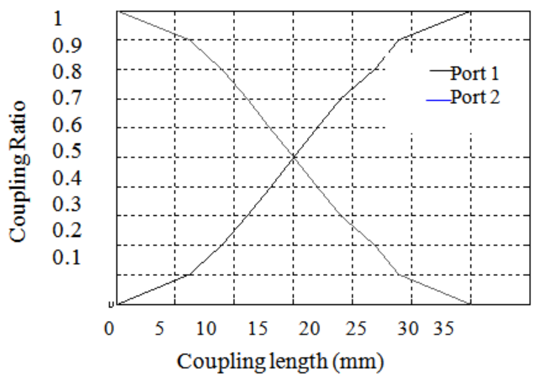

Figure 2: Coupling ratio Vs Coupling Length

It is evident from Fig. 2 that for 50:50 coupler the coupling length is 15 mm and for any other coupling ratio the coupling length of the coupler for d = 4.08 µm can found from Fig. 2

We have chosen the core spacing 4.08 µm, because it is the smallest distance that the present fabrication technology Micro structure polymer optical fiber supports. The presently available Silica fiber coupler uses a core spacing of 6 µm. As we have decreased the core spacing it will also cause to reduce the coupler losses.

Eq. 14~15 were simulated using MATLAB software and for various coupling ratio the simulated results are shown in the Table 1.

Table 1: Design Parameters Of Different Couplers.

Coupling ratio	Coupling length (mm)	Total length(mm)
50:50	15	19.4
45:55	14.1	18.5
40:60	13.1	17.5
35:65	12.1	16.5
30:70	11.1	15.5
25:75	10.0	14.4
20:80	8.9	13.3
15:85	7.6	12.0
10:90	6.2	10.6
5:95	4.3	8.7
1:99	1.9	6.3

From the table it can be observed that coupling length and total length of a coupler varies significantly with coupling ratio. Our goal is to design a 50:50 coupler in which the coupling length is 15 mm and total length is 19.4 mm.

Eqs. 9~11 and eq. 15are simulated for various core spacing. The result is shown as a plot of core spacing versus total length in fig. 3. it is clear from the fig. 3 that increasing the core spacing increase the coupler length significantly. The present fabrication technology support 4.08 μm core spacing

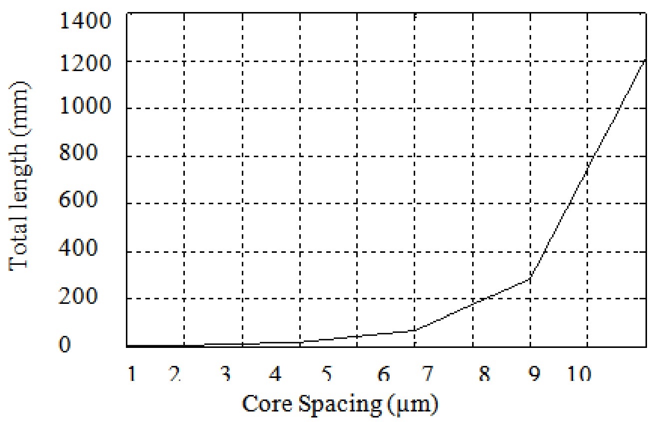

Figure 3: Total length Vs Core spacing.

Fig. 3 shows that total length of the coupler for 4.08 μm core spacing is 19.4 mm. This is comparatively very smaller than the coupler used at present. At present the total length of the coupler is around 70 mm.

Equations 4 ~ 6 had been simulated in MATLAB. The losses correspondence to different core spacing with a radius of curvature 15 mm of a 50:50 coupler is given in Table 2. The table shows Scattering loss, Absorption loss and Bending loss, which are not dominant loss in optical coupler. So we will not consider these losses for comparison.

Table 2: Losses Of A 50:50 Coupler For Different Core Spacing

Core spacing,d(μm)	Total coupler length (mm)	Scattering loss (μdB)	Absorption loss (μdB)	Bending loss dB
1	6.1	0.86	6.1	0.1329
2	7.9	1.12	7.9	0.1324
4.08	19.4	2.7	19.4	0.1313
6	69.9	9.96	69.9	0.1302
8	287.1	40.90	287.1	0.1291
10	1215.9	173.37	1215.9	0.1280

In our designed coupler the reflection of optical power is neglected. Hence return loss neglected in the designed coupler. Polarization Dependent Loss (PDL) is the ratio of the maximum and the minimum transmission of a coupler with respect to all polarization states. Normally this loss is measured experimentally after fabrication. Hence we did not consider PDL in the design. There is no cross talk in the designed coupler because we assumed that fabrication would be done without any defect. Finally we have simulated eqs. 1~3. The losses correspondence to different Coupling ratio is given in Table 3. The table shows the Insertion Loss and Excess Loss which are the main losses in Coupler and the results are compared with the presently used coupler parameters [16].

Table 3: Comparison Of A Typical Coupler And Our Designed Coupler.

Coupling ratio	Typical 2 x 2 coupler [1]		Our designed coupler	
	Insertion loss dB	Excess loss dB	Insertion loss db	Excess Loss dB
50:50	3.5/3.5	0.50	3.01/3.01	0.13
45:55	4.2/3.3	0.50	3.46/2.59	0.13
40:60	4.7/2.8	0.50	3.97/2.21	0.13
35:65	5.4/2.4	0.50	4.55/1.87	0.13
30:70	5.6/2.2	0.50	5.2/1.54	0.13
25:75	6.0/2.0	0.50	5.92/1.24	0.13
20:80	7.1/1.7	0.50	6.9/.961	0.13
15:85	7.9/1.3	0.50	8.2/.705	0.13
10:90	9.8/1.0	0.50	10/.457	0.13
5:95	11.3/.7	0.50	13.01/.22	0.13
1:99	23.5/.35	0.50	20/.044	0.13

Table 3 shows that the insertion losses and excess losses of our designed coupler are lower than the losses of the typical available coupler.

Conclusion

A technique for the design and analysis of single mode fiber optic couplers has been presented. A low loss optical coupler was designed and simulated with MATLAB software. Loss parameters were calculated for different coupling ratio and finally compared with the losses of presently available couplers. The comparison shows that our designed coupler has lower insertion and excess losses. The physical dimension of the designed coupler is also very short compared with the practical one. So it may be implemented in optical fiber network.

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