Simulation of an Optical Coupler Using Beam Propagation Method

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Abstract

Optical coupler is an important thing in a fiber optics system. In this paper, the simulation of an optical coupler is performed by Beam Propagation Method for Fiber (BPM 3DF). If two waveguides are sufficiently close such that their fields overlap, light can be coupled from one into the other. By using BPM 3DF, 2 linear waveguides as the fiber are designed, embedded in a wafer (cladding). 3 parameters are changed one by one; the length, the width and the height of the wafer and the fiber to define the exact parameters that can make the device acts as a 3dB coupler. By using 2250μm length, 35μm width and 22μm height, the program shows that half of optical power is transferred to fiber 2 so that the coupling ratio is 50:50. Besides, if the length is increased more than 2250μm, more than half of power is transferred to fiber 2 until it is transferred completely at a distance 4500μm. If more than 4500μm length, the power is interchanges continuously between fiber 1 and fiber 2. If the length is less than 2250μm, only small quantity of power is transferred. The same result would be observed if it is increased and decreased one by one of the parameters; the width of wafer or the height of wafer while other parameters are constant. If the width is more than 35μm or the height is more than 22μm while other parameters are constant, the power interchanges continuously between fiber 1 and fiber 2. While the width is less than 35 m or the height is less than 22μm, more than half of power is transferred to fiber 2. In this case, it is observed that there is a minimum width which is 17μm and the minimum height which is 9μm, whereby above that values, the program is executable. From the result, its shows that the length, the width and the height of the wafer and fiber are influenced the quantity of optical power through from one fiber to other fiber and can build a 3dB coupler.

Keywords: BPM 3DF, wafer, linear waveguide, coupled mode, optical power.

INTRODUCTION

The BPM 3D for Fibers program, which also call BPM 3DF, allows to design and simulate devices built from multilayer optical fibers. The main characteristics of the BPM 3DF layout concept (refer to Figure 1):

- The wafer in BPM 3DF is a cladding box in which design devices. Its length is along the presumed light propagation direction, Z, horizontal on the screen. Its width is along the discretization mesh in the X direction, vertical on the screen. Its thickness or height is along the discretization mesh in the Y direction, perpendicular to the screen and not shown on the layout interface.
- The cladding coordinate system, (X, Y, Z), has its origin at the beginning of propagation (Z=0), in the middle of the cladding width (X=0) and height (Y=0).
- The cladding length is the propagation distance, while the cladding width is the mesh width in the X direction. The cladding height is the mesh size in the Y direction.
- Fibers are embedded in the cladding box. In the design, the fibers can have different shapes and variable widths, but for each fiber its position in Y direction remains constant that is, the fiber center lays in a horizontal XZ plane.

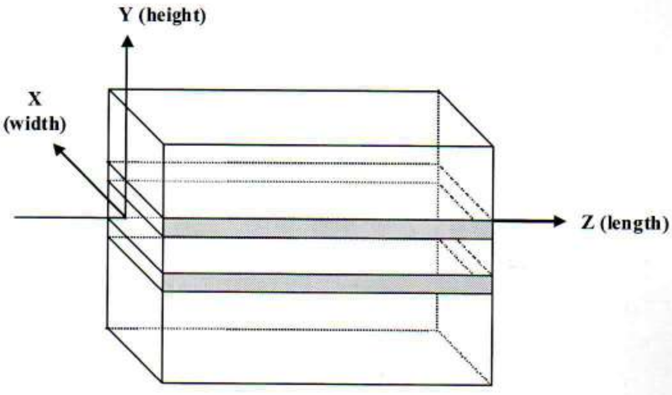


Figure 1 Cladding box with fibers

COUPLED MODE THEORY

If two waveguides are sufficiently close such that their fields overlap, light can be coupled from one into the other. Optical power can be transferred between the waveguides, an effect that can be used to make optical couplers and switches. Consider two parallel planar waveguides made of two slabs of widths d, separation $2a$, and refractive indices n_1 and n_2 embedded in a medium of refractive index n slightly smaller than n_1 and n_2, as illustrated in Figure 2. Each of the waveguides is assumed to be single-mode. The separation between the waveguides is such that the optical field outside the slab of one waveguide (in the absence of the other)

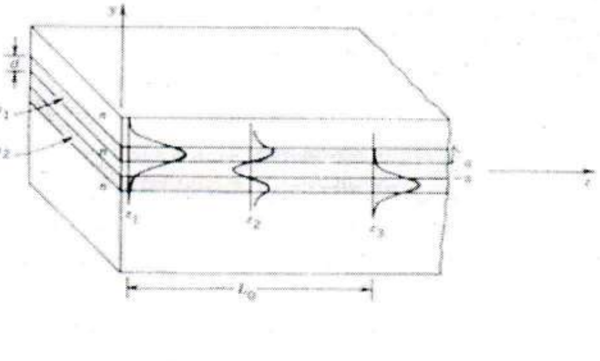


Figure 2 Coupling between 2 parallel planar waveguides. At z_1 light is mostly in waveguide 1, at z_2 it is divided equally between the 2 waveguides, and at z_3 it's mostly in waveguide 2

The coupled-mode theory assumes that the modes of each of the waveguides, in the absence of the other, remain approximately the same, say $u_1(y)$ exp $(-j\beta_1 z)$ and $u_2(y)$ exp $(-j\beta_2 z)$, and that coupling modifies the *amplitudes* of these modes without affecting their transverse spatial distributions or their propagation constants. The amplitudes of the modes of waveguides 1 and 2 are therefore functions of z, $a_1(z)$ and $a_2(z)$. The theory aims at determining $a_1(z)$ and $a_2(z)$ under appropriate boundary conditions.

Coupling can be regarded as a scattering effect. The field of waveguide 1 is scattered from waveguide 2, creating a source of light that changes the amplitude of the field in waveguide 2. The field of waveguide 2 has a similar effect on waveguide 1. An analysis of this mutual interaction leads to two coupled differential equations that govern the variations of the amplitudes $a_1(z)$ and $a_2(z)$.

It can be shown $a_1(z)$ and $a_2(z)$ are governed by two coupled first-order differential equations

$$\frac{da_1}{dz} = -j\wp_{21} \exp(j\Delta\beta z)a_2(z) \qquad (1)$$

$$\frac{da_2}{dz} = -j\wp_{12} \exp(-j\Delta\beta z)a_1(z)$$

Coupled Mode Equations (2)

where

$$\Delta\beta = \beta_1 - \beta_2 \qquad (3)$$

is the phase mismatch per unit length and

$$\wp_{21} = \frac{1}{2}\left(n_2^2 - n^2\right)\frac{k_0^2}{\beta_1}\int_a^{a+d} u_1(y)u_2(y)dy \qquad (4)$$

$$\wp_{12} = \frac{1}{2}\left(n_1^2 - n^2\right)\frac{k_0^2}{\beta_2}\int_{-a-d}^{-a} u_2(y)u_1(y)dy \qquad (5)$$

are coupling coefficients.

We see from Equation (2) that the rate of variation of a_1 is proportional to a_2 and vice versa. The coefficient of proportionality is the product of the coupling coefficient and the phase mismatch factor exp $(j\Delta\beta z)$.

Assuming that the amplitude of light entering waveguide 1 is $a_1(0)$ and that no light enters waveguide 2, $a_2(0) = 0$, then Equation (2) can be solved under these boundary conditions, yielding the harmonic solution

$$a_1(z) = a_1(0)\exp\left(+\frac{j\Delta\beta z}{2}\right)\left(\cos\gamma z - j\frac{\Delta\beta}{2\gamma}\sin\gamma z\right) \qquad (6)$$

$$a_2(z) = a_1(0)\frac{\wp_{12}}{j\gamma}\exp\left(-j\frac{\Delta\beta z}{2}\right)\sin\gamma z \qquad (7)$$

where

$$\gamma^2 = \left(\frac{\Delta\beta}{2}\right)^2 + \wp^2 \qquad (8)$$

and

$$\wp = \left(\wp_{12}\wp_{21}\right)^{1/2} \qquad (9)$$

The optical powers $P_1(z) \propto |a_1(z)|^2$ and $P_2(z) \propto |a_2(z)|^2$ are therefore

$$P_1(z) = P_1(0)\left[\cos^2\gamma z + \left(\frac{\Delta\beta}{2\gamma}\right)^2 \sin^2\gamma z\right] \qquad (10)$$

$$P_2(z) = P_1(0)\frac{|\wp_{12}|^2}{\gamma^2}\sin^2\gamma z \qquad (11)$$

Thus power is changed periodically between the two guides as illustrated in Figure 3. The period is $2/\gamma$.

Power conservation requires that $\wp_{12} = \wp_{21} = \wp$.

When the guides are identical, i.e., $n_1 = n_2$, $\beta_1 = \beta_2$, and $\Delta\beta = 0$, the two guides waves are said to be phase matched. Equations (10, 11) then simplify to

$$P_1(z) = P_1(0)\cos^2\wp z \qquad (12)$$

$$P_2(z) = P_1(0)\sin^2\wp z \qquad (13)$$

The exchange of power between the waveguides can then be complete, as illustrated in Figure 4.
Thus a device for coupling desired fractions of optical power from one waveguide to another. At a distance $z = L_0 = \pi/2\wp$, called the transfer distance, the power

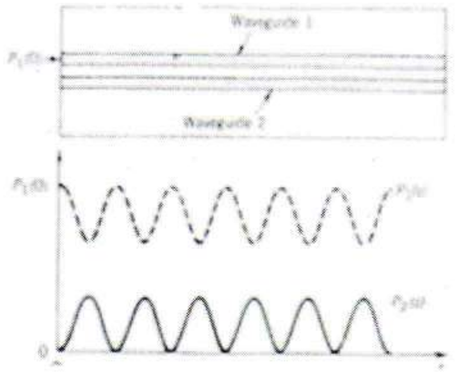


Figure 3 Periodic exchange of power between guides 1 and 2

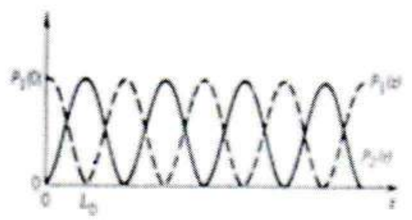
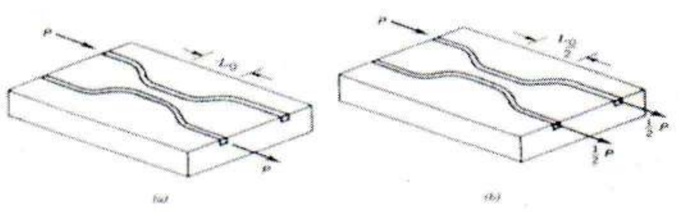


Figure 4 Exchange of power between guides 1 and 2 in the phase-matched case

is transferred completely from waveguide 1 to waveguide 2 (Figure 5a). At a distance $L_0/2$, half the power is transferred, so that the device acts as a 3-dB coupler, i.e., a 50/50 beam splitter (Figure 5b).

Figure 5 Optical couplers: (a) switching of power from one waveguide to another; (b) a 3dB coupler



Results and Discussion

This program has studied about how to simulate a fiber coupler. A cladding box is designed which also called wafer and used 2 linear waveguides as the fiber with the following data (Figure 6):

Parameters	Cladding	Linear Waveguide
Length, Z	2250μm	2250μm
Width, X	35μm	6μm
Height, Y	22μm	6μm
Wavelength, λ	1.33μm	1.33μm
Refractive Index, N	1.372	1.4

where the refractive index for cladding, n is 1.372 while fiber coupler, n_1 and n_2 are 1.4 where $n < n_1$ and n_2.

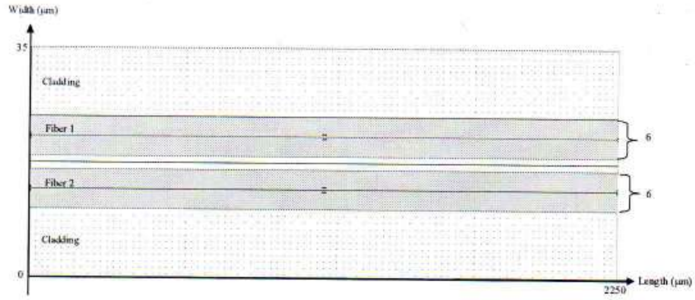


Figure 6 Layout the fiber embedded in a wafer (cladding box) with their length and width

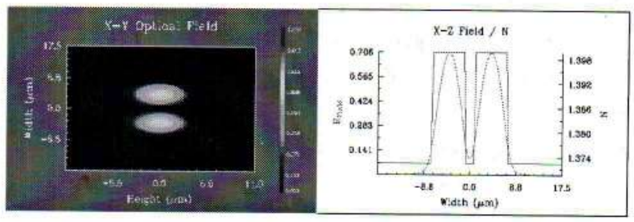


Figure 7 (a)

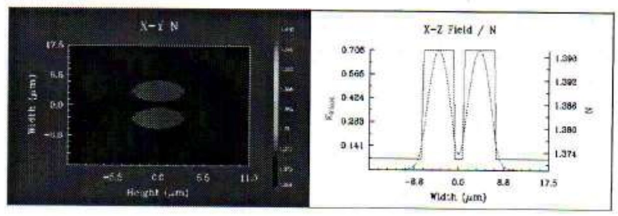


Figure 7 (b)

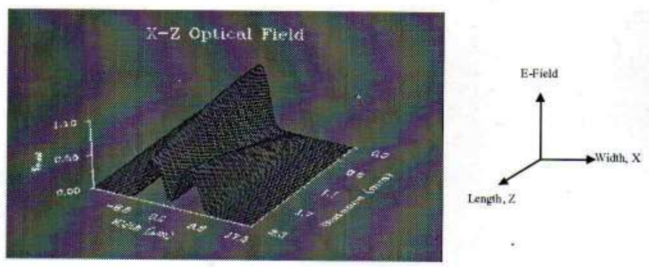


Figure 7 (c)

Figure 7 The display shows the optical field and effective index after running the program.
(a) the left one is X-Y optical field; a color map of propagating field while the right one is X-Z optical field and X-Z refractive index N; X-Z cuts at a given distance of propagation

(b) the left one is X-Y refractive index N; a color map of the index cross-section while the right one is X-Z optical field and X-Z refractive index N
(c) X-Z optical filed, X-Z cut versus propagation distance

Figure 7 shows that when the light through the fiber, the optical signal is coupled from one fiber to other fiber. In the end of fiber at a distance 2250μm, half the optical power is transferred, so that the device acts as a 3-dB coupler. If the length of wafer and fiber increased until 4500μm while the width and the height of wafer and fiber still constant, the power is transferred completely from fiber 1 to fiber 2 (Figure 8). Otherwise, if the length is less than 2250μm, only small quantity of power is transferred to fiber 2. While the length is more than 4500μm, the power interchanges continuously between fiber 1 and fiber 2. In this case, the minimum length for power transfer to fiber 2 is 200μm, but if the length is less than 200μm, for the same power transfer, the propagation steps must be shorten or the number of displays should be reduced. Figure 9 shows that the influence of the length of the wafer and also the length of the fiber on the optical power. As can be expected, the exchange of power between fiber 1 and fiber 2 can then be almost 100% as illustrated in Figure 9.

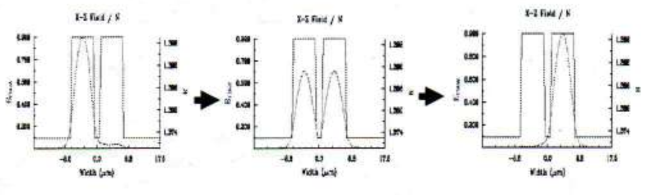


Figure 8 The power is transferred completely from fiber 1 to fiber 2 at a distance 4500μm
Figure 9 Relation between the length and the optical power

On the other hand where the height and the length are constant; the width of the wafer is increased more than 35μm, the optical power interchanges continuously between fiber 1 and fiber 2. While if the width is less than 35μm, more than half of the power is transferred to fiber 2. The minimum of width is 17μm but if the width is less than 17μm, no fundamental mode is detected and it might be due to the limitation of the computational software.

The same result would be observed if the width and the length are constant; the height of the wafer is increased more than 22μm, the optical power interchanges continuously between fiber 1 and fiber 2. While if the height is less than 22μm, more than half of power is transferred to fiber 2. It is observed that there is a minimum height which is 9μm, whereby above that value, the program is executable.

CONCLUSION

In conclusion, the results describe that the length, the width and the height of the cladding and the fiber will influence how much the optical power transfer between two waveguides. At a distance 2250μm with 35μm width of wafer and 22μm height of wafer, 50% optical power is transferred to fiber 2 achieving a coupling ratio of 50:50 and thus a 3dB coupler is obtained.

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