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A novel opinion about the coupling loss between single-mode fibers and waveguides

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A detailed analysis is presented, about the coupling loss dependence on the waveguide mode eccentricity and symmetry between single-mode fibers and waveguides. A new conclusion is obtained that more symmetric waveguide mode leads to lower coupling loss, but less eccentric waveguide mode does not always mean low coupling loss, which depends on the waveguide mode depth.

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1. Introduction

With the development of integrated optics, the problem of reducing the coupling loss between waveguide devices and single-mode optical fibers has received increased attention. There are several causes of coupling loss between a fiber and a waveguide[1-3], which includes mode field mismatch, propagation loss, Fresnel loss and misalignment loss. Mode field mismatch contributes significantly to interconnect loss[3-6].

There have been investigated about the mode-field mismatch in the literatures [2-3,7]. It has been found that the less eccentric and the more symmetric the guided mode size, the lower will be the mode field mismatch loss (in general, the fiber mode is assumed to be circular)

But in this work, it seems that less waveguide mode eccentricity does not always mean lower coupling loss.

2. Theory

The coupling η between the fiber mode E_1 and the guided mode E_2 is given by the well-known equation: [8]

$$\eta = \frac{\left| \int_{-\infty}^{\infty} E_1(x,y) E_2^*(x,y)\, dxdy \right|^2}{\int_{-\infty}^{\infty} |E_1|^2 dxdy \int_{-\infty}^{\infty} |E_2|^2 dxdy} \qquad (1)$$

where E_1 and E_2 are the electric-field distributions of the fiber and the waveguide, x is normal to the direction of propagation in the plane of the substrate, y is normal to the substrate surface, and z is the direction of propagation.

Single-mode fiber is well approximated by a circular Gaussian function [1,2,9]

$$E_1(x,y) = \exp(-(x^2 + y^2)/r_f^2) \qquad (2)$$

where r_f is the radius at which the fiber mode field amplitude is equal to e^{-1}.

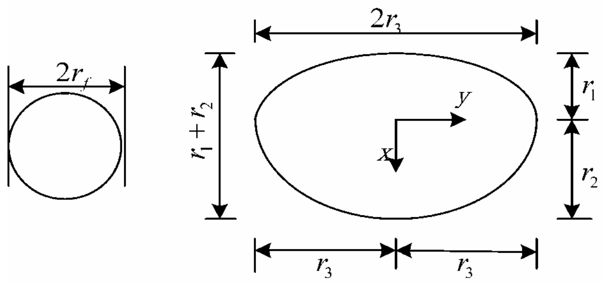

Fig. 1. Fiber mode profile and waveguide mode profile.

The waveguide mode profile is expressed by the combination of two half-Gaussians in the depth (y) direction [1,2,9] (see Fig. 1):

$$E_2(x,y) = f(x) \cdot g(y) \qquad (3)$$

where $$f(x) = F_0 \exp(-x^2/r_3^2) \qquad (4)$$

and $$g(y) = \begin{cases} G_0 \exp(-y^2/r_1^2), y \le 0 \\ G_0 \exp(-y^2/r_2^2), y \ge 0 \end{cases} \qquad (5)$$

Substitution of (2)-(5) into (1) gives the expression in terms of the modal parameters:

$$\eta = \frac{4\left(\left(\frac{1}{r_f^2}+\frac{(1+e)^2}{r_d^2}\right)^{-\frac{1}{2}}+\left(\frac{1}{r_f^2}+\frac{(1+e)^2}{e^2 r_d^2}\right)^{-\frac{1}{2}}\right)^2}{a\left(r_d^2+\frac{4}{a^2}r_f^2\right)} \qquad (6)$$

where $a=\frac{2r_3}{r_1+r_2}$ is the waveguide mode eccentricity, $e=\frac{r_1}{r_2}$ is the waveguide mode asymmetry, $r_d=r_1+r_2$ is the depth of waveguide mode.

The optical waveguide is always fabricated by the diffused methods [10-11].Thus, it is practical that a>1($2r_3$> $r_d=r_1+r_2$ is caused by the side diffusion [12]) and e<1[2,12-14] ($r_1<r_2$ reflects the asymmetry of the index profile in the depth direction [12]).

3. Results and discussion

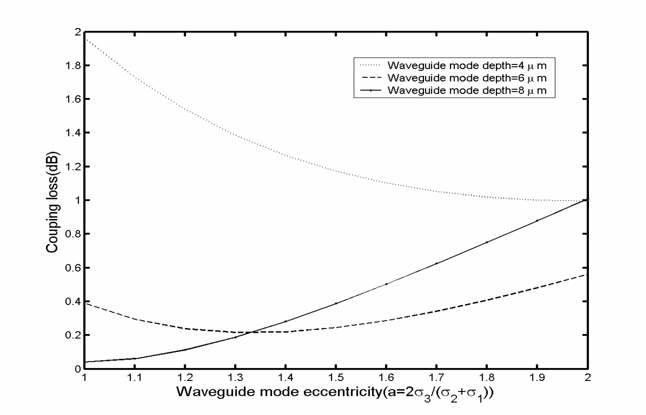

Fig. 2. Coupling loss (per interface) versus waveguide mode eccentricity for the waveguide mode depth (4μm, 6μm and 8 μm) with the fiber mode diameter 8 μm and waveguide mode asymmetry 0.6.

Fig. 2 is the calculated coupling loss (per interface) versus waveguide mode eccentricity for waveguide mode asymmetry 0.6 and fiber mode diameter 8μm with different waveguide mode depths (4 μm, 6 μm and 8 μm).

As indicated in Fig. 2, when the waveguide mode eccentricity is close to a=1, the coupling loss becomes high for the waveguide mode depth=4μm, the coupling loss becomes low first and high later for the mode waveguide depth=6μm, but the coupling loss becomes low for the waveguide mode depth=8μm.

Fig. 3 is the calculated coupling loss (per interface) versus waveguide mode eccentricity with different waveguide mode asymmetry. The waveguide mode is always smaller than the mode of the fiber [2-3].So Fig. 3(a) is for waveguide mode depth 4 μm and fiber mode diameter 8 μm, Fig. 3(b) is for waveguide mode depth 6μm and fiber mode diameter 8 μm, and Fig. 3(c) is for waveguide mode depth 8μm and fiber mode diameter 8μm.

The results in Fig. 3 indicate that, regardless of the waveguide mode depth and eccentricity, the small waveguide mode asymmetry always has less coupling loss. However, there is a significant difference about the coupling loss dependence on the waveguide mode eccentricity among Fig. 3(a), Fig. 3(b) and Fig. 3(c) for different waveguide mode depths. In Fig. 3(a) the small waveguide mode eccentricity get the high coupling loss, but in Fig. 3(c) the small waveguide mode eccentricity means the low coupling loss, and the results are different with the others in Fig. 3(b).

So, the small waveguide mode asymmetry always has less coupling loss. But the small waveguide mode eccentricity does not always mean the low coupling loss, which depends on the waveguide mode depth.

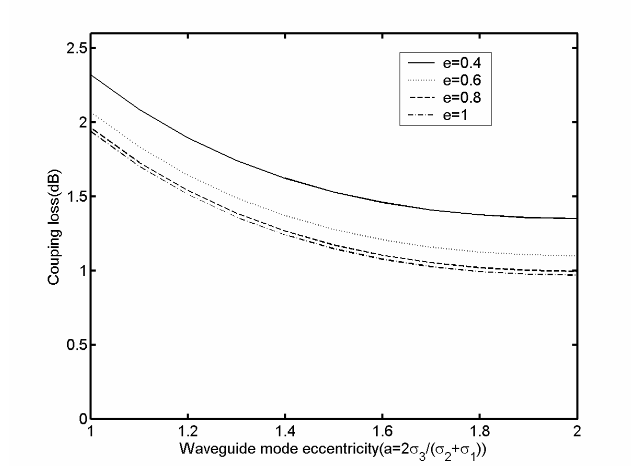

Fig. 3(a). waveguide mode depth 4 μm and fiber mode diameter 8 μm.

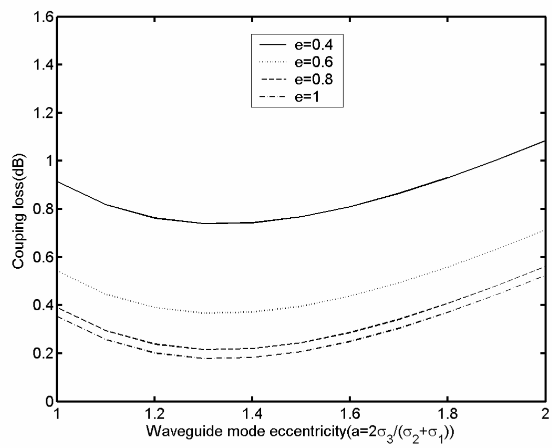

Fig. 3(b). waveguide mode depth 6 μm and fiber mode diameter 8 μm.

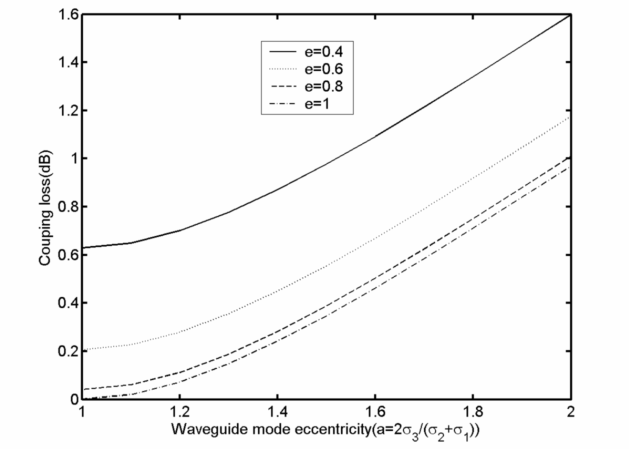

Fig. 3(c). Waveguide mode depth 8μm and fiber mode diameter 8μm.

Fig. 3. Coupling loss (per interface) versus waveguide mode eccentricity for the waveguide mode asymmetry(e=0.4,0.6,0.8,1.0).

4. Conclusion

In conclusion, the waveguide mode eccentric and symmetric dependence of the coupling loss has been analyzed. It has been found that the more symmetric the mode size, the lower will be the coupling loss, but less eccentric mode does not always mean low coupling loss, which depends on the waveguide mode depth.

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