Analysis of the Fiber-Waveguide Coupling Efficiency and the Resulting Polarization Dependent Loss

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***Abstract*—In both science research and product development of waveguides based chips fiber-waveguide coupling is a mandatory stage. In this work, the universal fiber-waveguide coupling efficiency is analyzed based on the overlap model of fiber and waveguide profiles. Furthermore, the systematic numerical simulations with gap size, matching material and birefringence show that the waveguide-gap interface reflection plays a dominant role in polarization dependent loss (PDL). For the two cases: this interface reflection is (i) involved and (ii) eliminated, the resulting numerical PDL values are 1.08dB and 0.06dB, respectively. The simulations from the professional simulators are sustainable to the above numerical results.**

Keywords: fiber-waveguide coupling efficiency; TE/TM-mode; polarization dependent loss

I. INTRODUCTION

The fiber-waveguide coupling is one of the most popular work in experimental and testing processes of waveguide based projects. So, in the past two decades the coupling behaviors and coupling efficiency have been investigated and some special methods are developed such as the prism coupling and the grating-assistant coupling [1]. Consequently, for the large -size silica-waveguides, the fiber-waveguide butt coupling loss has improved an extremely low level.

In the past decade, after the silicon-on-insulator (SOI) waveguide based photonic integrated circuits and silicon waveguide photonic components impressed the scientists and engineers in the fields of information technology and optoelectronic communication networks, the coupling and other physical processes of the small size waveguides and the unregular-shape waveguides are the important issues in projects. So, the fiber-waveguide butt-coupling has also attracted much more research works and both the transverse grating-assistant coupling and the horizontal grating-assistant coupling were also published in some high-impact journals including Nature Photonics. However, no much efforts have been paid to investigating the polarization dependence of the fiber-waveguide coupling process. Thereby, with this work, we want to fulfill this vacancy - the polarization dependent loss (PDL) of fiber-waveguide butt coupling of large-size waveguide based optical circuits by starting with the theoretical model for the mode-coupling of two guided-channels, the numerical and software simulations.

II. MODELING FOR FIBER-WAVEGUIDE COUPLING PROCESS

In the models of fiber-waveguide coupling based on the overlap of two guided-modes, there are two key physical parameters: (i) the electric-field profiles of waveguide-mode and fiber-mode and (ii) the reflection of waveguide-gap interface. So, we investigate the coupling efficiency and the PDL with these two factors.

A. Analysis for the fiber-waveguide butt coupling samples

The functional principle of fiber-waveguide coupling is the overlap efficiency between the optical guided-modes of fiber and waveguide, so an overlap integral equation is the theoretical model. Figure 1 shows a schematic configuration of the overlap form of the fiber mode and waveguide mode [1].

After considering the mode divergences of fiber and waveguide, the overlap integral can be defined by: [2]

$$\Gamma_{WF} = \left| \frac{\iint E_{WG}(x,y) E_{fib}(x,y)^2 \, dxdz}{\iint \left|E_{WG}(x,y)\right|^2 dxdy \iint \left|E_{fib}(x,y)\right|^2 dxdy} \right| \tag{1}$$

Where $E_{WG}(x,y)$ and $E_{fib}(x,y)$ stand for the electric-vector amplitudes of optical guided-modes from waveguide and fiber, respectively. In this work, in order to obtain the precision distribution of waveguide mode output electric-field we use a professional software – BPM to read the precision values of electric amplitudes of waveguide mode to calculate the coupling efficiency defined by (1).

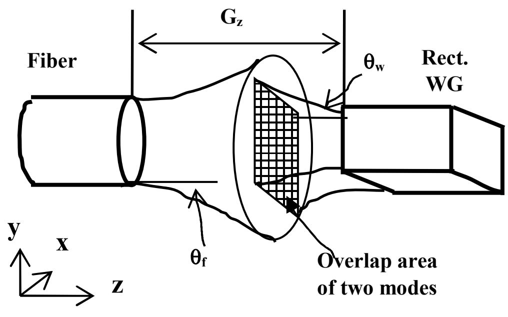

Figure 1 Perspective view of schematic configuration of the mode-overlap in fiber-waveguide coupling process.

B. *Discussion for the mode profiles of waveguide and fiber*

In discussion of field distributions of waveguide and fiber modes in the coupling process, the divergent angles of these two fields must be taken into account. Here we only need to consider the waveguide mode when it comes out from waveguide end. In the system shown in Fig. 1 the radiation of the guided-mode is respect to the Fresnel-Kirchhoff diffraction formula [3]. So, at the input plane z=0, the distribution function of electric field is approximated to be:

$$f_0(x_0, y_0, z=0) = \exp[-(x_0^2 / w_x^2 + y_0^2 / w_y^2)] \qquad (6)$$

Where w_x and w_y are the mode sizes defined by $1/e$. If the z plane is in the Fraunhofer region (6) is evolved to the form:

$$f(x, y, z) = \sqrt{\frac{w_x w_y}{W_x W_y}} A \exp[-(\frac{x^2}{W_x^2} + \frac{y^2}{W_y^2})] - jV(x, y, z) \qquad (7)$$

With the three expressions:

$$V(x, y, z) = k_0 n_{gap} (\frac{x^2}{2z} + \frac{y^2}{2z} + z) - \frac{\theta_x + \theta_y}{2} \qquad (8a)$$

$$W_x(z) = 2z/(n_{gp} k_0 w_x), \; W_y(z) = 2z/(n_{gp} k_0 w_y) \qquad (8b)$$

$$\theta_x = \sin^{-1}(2/n_{gp} k_0 w_x), \; \theta_y = \sin^{-1}(2/n_{gp} k_0 w_y) \qquad (8c)$$

Where θ_x and θ_y are the divergent angles, at the x and y coordinates, respectively.

For the Corning single-mode SMF-28, we first have the half effective width 5.25μm of output mode, the spot size is defined as $w_r(0)$ set by $1/e^2$ for output power distribution, then obtain the spot size: $w_r = \sqrt{\ln(2)/2} w_r(0)$ [4].

At the fiber end, the optical power profile $U_0(r)$ and divergent angle θ_r of fiber mode are defined by:

$$U_0(r) = A \exp(-r_0^2 / 2w_r^2), \; \theta_r = \sin^{-1}(2/n_{gp} k_0 w_r) \qquad (9)$$

Where A is the normalization constant.

For a polarization p, the amplitude reflection coefficient R_p at the interface of waveguide and gap is defined by [5]:

$$R_p = \frac{\eta^{2p} \cos\theta - (\eta^2 - \sin^2\theta)^{1/2}}{\eta^{2p} \cos\theta + (\eta^2 - \sin^2\theta)^{1/2}} \qquad (10)$$

Where $p=0$ for TE-mode and $p=1$ for TM-mode, and $\eta = N_{eff}/n_{gp}$ (N_{eff} the effective refractive index of waveguide and n_{gp} the refractive index of gap material). Here we only consider the roughness σ of waveguide-gap interface, the attenuation factor induced by this roughness scattering process can be expressed as $F_\sigma = \exp[-(k_o n_{gp} \sigma \cos(\theta)]$. Therefore, the fiber-waveguide coupling efficiency has two cases: (i) not considering and (ii) considering σ impact.

For the 0.75% index contrast silica-waveguide, the channel size: 6.0x6.0μm^2 and the refractive indices of the core and cladding: 1.4553 and 1.4444, with the software BPM we obtain the effective indices of TE-mode and TM-mode as: $N_{eff}(TE) = 1.450846$ and $N_{eff}(TM) = 1.449844$.

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III. SIMULATION FOR COUPLING EFFICIENCY AND PDL

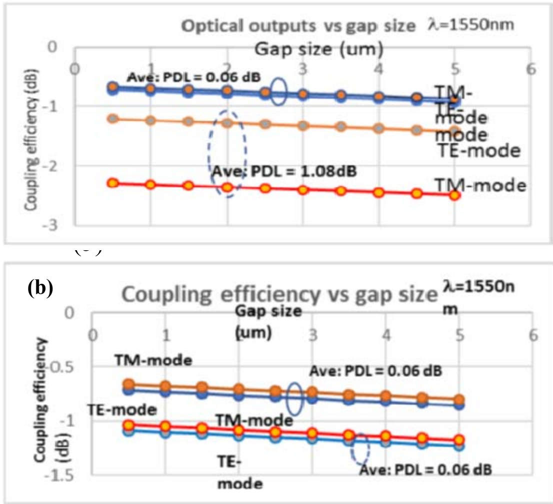

Figure 2. Numerical calculation results for the fiber-waveguide coupling efficiency with gap size for two cases: (a) the air gap; (b) the matching gel gap.

By setting $\sigma = 100nm$ we obtain the numerical results of the fiber-waveguide coupling efficiency versus the gap size for two gap materials ($n_{gp} = 1.0$ and $n_{gp} = 1.4500$) as shown in Fig. 2 where (a) has no the waveguide-gas interface reflection, while (b) has the waveguide-gas interface reflection. Note that the Fresnel reflection of waveguide-gap interface can increase PDL from 0.06dB to 1.08dB, but it can be eliminated by using either a low-reflection interface or a matching gel. With OptiwaveBPM and R-Soft Beamprop simulators, we obtain PDL values as 0.09dB and 0.05dB, respectively, which are sustainable to the above numerical results.

IV. CONCLUSION

The powerful modeling and efficient simulations for the fiber-waveguide coupling caused PDL in this work are very significant to clearly analyze and address the PDL values when designing and testing the PLC devices.

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