Optics and Photonics Journal, **2011, 1, 106-109**
doi:10.4236/opj.2011.13018 Published Online September 2011 (http://www.SciRP.org/journal/opj)

Optical Properties of the Coupling Interface for Planar Optical Waveguides

Yu Zheng[1,2], **Ji-An Duan**[1,2]
[1]*College of Mechanical & Electrical Engineering*, *Central South university*, *Changsha*, *China*
[2]*StateKey laboratory of High Performance and Complex Manufacturing*, *Changsha*, *China*
E-mail: *zhengyu@csu.edu.cn*

Received July 15, 2011; *revised August* 18, 2011; *accepted August* 29, 2011

Abstract

Planar optical waveguides are the key elements in a modern, high-speed optical network. An important problem facing the optical fiber communication system, specifically planar optical waveguides, is coupling. The current study presents a coupling model for planar optical waveguides and optical fibers. The various effects of the optical properties of the coupling interface were analyzed by the scalar finite difference beam propagation method, including the thickness, with or without the matching refractive index of the interface adhesive. The findings can serve as a guide for planar optical waveguide packaging.

Keywords: Planar Optical Waveguide, Coupling Interface, Beam Propagation, Optical Property

1. Introduction

Planar optical waveguides refer to the fabrication and integration of several optical components on a common planar substrate, such as beam splitters, optical switchers, variable attenuators, interleave filters, and wavelength multiplexers [1,2]. Planar optical waveguides have the advantages of low transmission loss, low connection loss to optical fibers, compact size, high reliability, and high reproducibility. They stand at the frontier of development and can provide important support to the next generation of optical information technology.

Planar optical waveguide packaging involves bonding dozens or even hundreds of optical channels, with cross-sections of 4 × 4 μm to 8 × 8 μm, to single mode optical fibers, with a core diameter of 8 - 9 μm, as shown in **Figure 1**. Different bonding methods to connect the planar optical waveguides to the optical fibers, such as adhesives, welding, soldering, metal oxide bonding, and anodic bonding, have been tested in planar optical waveguide packaging [1,3-5]. Among the bonding methods, ultraviolet (UV)-cured adhesives offer several advantages, such as low cost, strong bonding, and excellent reliability.

UV-cured adhesives have two functions: to bond planar optical waveguides and optical fibers together, and to act as a light propagation medium in optical paths [4]. As a bonder, adhesives should provide strong and stable adhesion, and maintain their mechanical properties at a certain level while avoiding failure under all the conditions in an optical fiber communication system. As a light propagation medium, adhesives should be transparent at the wavelength used for optical fiber communication and be able to combine a wide range of wavelengths and optical power with long-term stability. Unfortunately, the optical properties of the coupling interface between a planar optical waveguide chip and the optical fibers are sensitive to adhesive properties (e.g., adhesive thickness, refractive index, and shrinkage of adhesive). Therefore, in this paper, the various effects of the optical properties of coupling interface are analyzed by the scalar finite difference beam propagation method, including the thickness of the interface adhesive, with or without the matching refractive index of the adhesive.

2. Scalar Beam Propagation Analysis

The beam propagation method is a particular approach

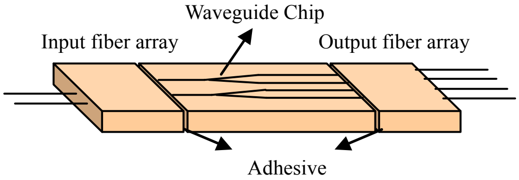

Figure 1. Schematic illustration of a planar optical waveguide packaging.

for approximating the exact wave equation for monochromatic waves and solving the resulting equation numerically. For the monochromatic type of waves, such as $\phi(x,y,z)\exp(-i\omega t)$, in a three-dimensional waveguide, the beam propagation method satisfies the scalar equation as follows [6,7]:

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}+\frac{\omega^2}{c^2}n^2(x,y,z)\phi=0 \tag{1}$$

where z is the propagation direction of waves, ω is the angular frequency, $n(x,y,z)$ is the refractive index of the incident medium, $k(x,y,z)=k_0 n(x,y,z)$ is introduced for the spatially-dependent wave number, and k_0 is the wave number in free space. If $\phi(x,y,z)=u(x,y,z)\exp(ik_n z)$, then k_n is the constant number to be chosen to make $u(x,y,z)$, where z is slowly varying. $\mathrm{d}^2u/\mathrm{d}z^2$ can then be neglected with respect to $k\mathrm{d}u/\mathrm{d}z$. With this assumption and after a slight rearrangement, the above equation is reduced to the following:

$$\frac{\partial u}{\partial z}=\frac{i}{2k_n}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\left(k^2-k_n^2\right)u\right) \tag{2}$$

The three propagation media in the coupling interface between the planar optical waveguide chip and optical fibers are the core of the optical fiber, adhesive, and core of the planar optical waveguide chip. To facilitate calculation, only the electric field *E* is considered. The magnetic field *H* can be calculated in the same way as the electric field *E*. The propagation field may be discontinuous in the coupling interface. The boundary can be given by:

$$\begin{aligned} E_1\times n &= E_2\times n \\ D_1\cdot n &= D_2\cdot n \end{aligned} \tag{3}$$

where n is the normal direction of input light, E_1 and E_2 are the electric field of the first and second media, respectively, and D_1 and D_2 are the electric flux density of the first and the second media, respectively.

3. Results and Discussion

The light coupling between a planar optical waveguide chip and an optical fiber can be calculated by the overlap integral of the optical field distributions in a reference plane. As the goal of the present study is to understand the properties of the coupling interface for planar optical waveguide packaging, a sample model, as shown in **Figure 2**, is used to investigate them. The proposed model presents the majority case in planar optical waveguide packaging. It consists of a single mode fiber, a regular square-type planar optical waveguide cross-section, and an adhesive with the thickness of d in between. The refractive index of the fiber core and cladding is 1.4494 and 1.445, respectively, at a wavelength of 1.31 μm (Δ = 0.3%). The refractive index of the planar optical waveguide core and cladding is 1.4486 and 1.445, respectively, (Δ = 0.25%) [2,8]. The diameter of the fiber core is 8.2 μm, and the planar optical waveguide core dimension is 8 × 8 μm. The adhesive has excellent transmittance at a wavelength of 1.26 - 1.65 μm, which is the optical communication wavelength.

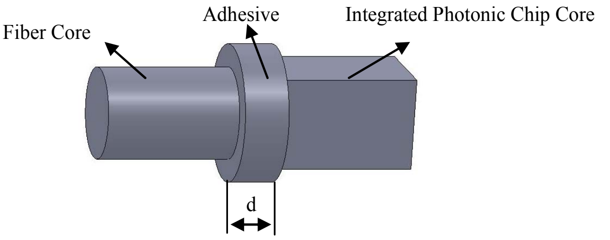

Figure 2. Model for the optical fiber-planar optical waveguide coupling simulation.

The coupling loss at the coupling interface is calculated using the scalar BPM algorithm. The coupling loss in optical power through a connection is defined similarly to that of signal attenuation through a waveguide. Coupling loss is also a log relationship. The coupling loss (*C.L.*) in optical power through a connection is defined as:

$$C.L.=-10Log_{10}\frac{P_i}{P_o} \tag{4}$$

P_o is the power emitted from the source optical waveguide in a connection. P_i is the power accepted by the connected optical waveguide. In any fiber optic connection, P_o and P_i are the optical power levels measured before and after the joint, respectively.

3.1. Refractive Index and Thickness of Adhesive

Figure 3 shows the coupling loss of an optical fiber and a planar optical waveguide chip with respect to the refraction index of the adhesive for different adhesive thicknesses. The present study assumes that no lateral misalignment and angular misalignment exist between the optical fiber and the planar optical waveguide chip. Moreover, the propagation wavelength is considered 1.31 and 1.55 μm (optical communication wavelength). In **Figure 3(a)**, at a wavelength of 1.31 μm, the coupling loss is less than 0.12 dB for the adhesive thickness of less than 9 μm. When the adhesive thickness is greater than 9 μm, the slope of the variation is large. In **Figure 3(b)**, at a wavelength of 1.55 μm, the coupling loss is less than 0.01 dB for various adhesive thicknesses, and the slope of the variation is small.

As shown in **Figure 3(a)** and **(b)**, a large adhesive

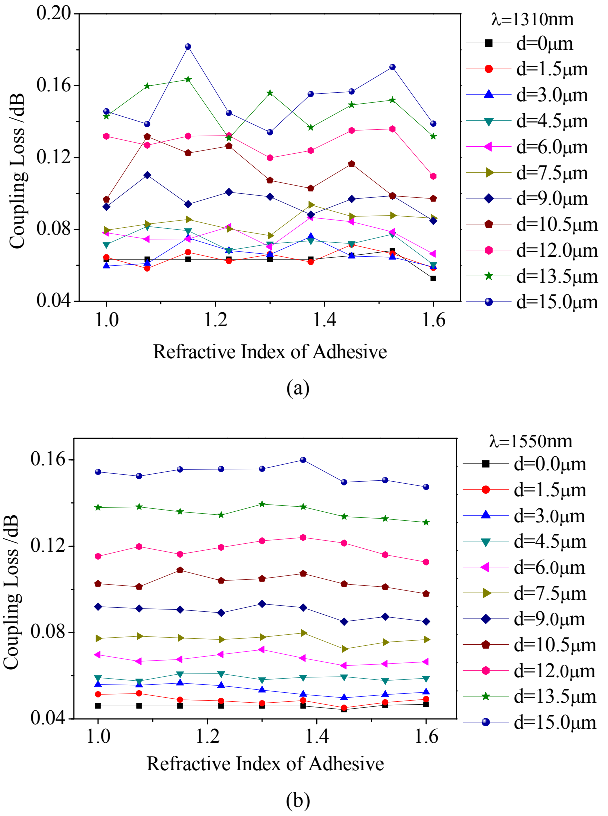

Figure 3. Calculated coupling loss vs. index and thickness of adhesive. (a) $\lambda = 1.31$ μm; (b) $\lambda = 1.55$ μm.

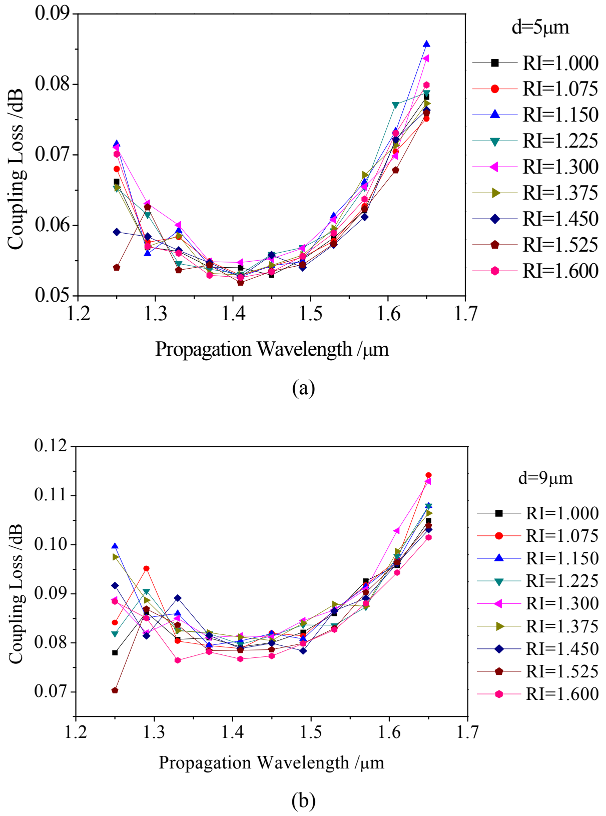

Figure 4. Calculated coupling loss vs. propagation wavelength. (a) Adhesive thickness $d = 5$ μm; (b) Adhesive thickness $d = 9$ μm.

thickness leads to a high coupling loss; upon increasing the adhesive thickness from 0 to 15 μm, the coupling loss increases about 60%. **Figure 3** shows that coupling loss is not equal to 0 when the adhesive thickness is 0. This finding is due to the non-matching mode fields of the optical fiber and the planar optical waveguide chip; the optical fiber core is round, whereas the planar optical waveguide chip is square. The coupling loss of an optical fiber and a planar optical waveguide chip is no more than 0.1 dB per coupling point. Thus, controlling the adhesive thickness at less than 10 μm is recommended. Furthermore, coupling loss is not sensitive to the refractive index of the adhesive if the adhesive thickness is less than 10 μm.

3.2. Propagation Wavelength

Figure 4 shows the relationship between propagation wavelength and coupling loss with different refractive indexes of the adhesive when the adhesive thickness is 5 and 9 μm. As the adhesive thickness increases, so does the coupling loss. Wavelength-dependent loss (WDL) is linked to the uniformity of coupling loss in the considered spectral bandwidth. It is defined as the difference in dB between the maximum and minimum values of coupling loss due to the variation of the propagation wavelength. WDL is calculated as follows:

$$\text{WDL (dB)} = C_{Lmax}\ \text{(dB)} - C_{Lmin}\ \text{(dB)} \quad (5)$$

Figure 4(a) shows that for the adhesive thickness of 5 μm, the WDL is no more than 0.09 dB, whereas the refractive index of the adhesive changes from 1.00 to 1.60. When the adhesive thickness is 9 μm, as shown in Figure 4 (b), the WDL is no more than 0.12 dB, whereas the refractive index of the adhesive changes from 1.00 to 1.60. According to GR-1221-CORE, the coupling loss changes no more than 0.2 dB over a full optical spectrum from 1.260 - 1.625 μm [9]. This finding indicates that the refractive index of the adhesive has little effect on the WDL of the planar optical waveguides.

4. Conclusions

The various effects of the optical properties of the coupling interface between a planar optical waveguide and optical fibers are analyzed by the scalar finite difference beam propagation method, including the thickness of the interface adhesive, with or without the matching refractive index of the adhesive. The following can be concluded:

- A large adhesive thickness leads to high coupling loss. Upon increasing the adhesive thickness from 0 to 15 µm, the coupling loss increases about 60%.
- The coupling loss of an optical fiber and a planar optical waveguide chip is no more than 0.1 dB per coupling point. Thus, controlling the adhesive thickness at less than 10 µm is recommended.
- The refractive index of the adhesive has little effect on the wavelength-dependent loss of planar optical waveguides when the refractive index of the adhesive changes from 1.00 to 1.60.

5. Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 50735007 and No. 51075402), and the National High-Tech Research and Development Program of China (Contract No. 2007 AA04Z344).

6. References

[1] Z. Q. Pan, C. Y. Yu and A. E. Willner, "Optical Performance Monitoring for the Next Generation Optical Communication Networks," *Optical Fiber Technology*, Vol. 16, No. 1, 2010, pp. 20-45. doi:10.1016/j.yofte.2009.09.007

[2] M. Kawachi, "Silica Waveguides on Silicon and Their Application to Integrated-Optic Components," *Optical and Quantum Electronics*, Vol. 22, No. 5, 1990, pp. 391-416. doi:10.1007/BF02113964

[3] S. H. Tao, "Optical Coupling and Splitting with Two Parallel Waveguide Tapers," *Optics Express*, Vol. 19, No. 2, 2011, pp. 906-912. doi:10.1364/OE.19.000906

[4] G. Z. Xiao, Z. Y. Zhang and C. P. Grover, "Adhesives in the Packaging of Planar Lightwave Circuits," *International Journal of Adhesion and Adhesives*, Vol. 24, No. 4, 2004, pp. 313-318. doi:10.1016/j.ijadhadh.2003.11.003

[5] K. W. Cheng, M. A. Uddin, H. P. Chan, *et al.*, "Optical Alignment Tolerances in Double-Side Irradiated Self-Written Waveguide-Induced Fiber Arrays Packages," *Optics Communications*, Vol. 283, No. 13, 2010, pp. 2669- 2675. doi:10.1016/j.optcom.2010.02.049

[6] S. A. Shakir, R. A. Motes and R. W. Berdine, "Efficient Scalar Beam Propagation Method," *IEEE Journal of Quantum Electronics*, Vol. 47, No. 4, 2011, pp. 486-491. doi:10.1109/JQE.2010.2091395

[7] Z. L. Xu and Y. Zheng, "Thermal-Stress Analysis of the Adhesive Bonding between the Planar Optical Waveguides Based on Finite Element Method," *Acta Photonica Sinica*, Vol. 39, No. 4, 2010, pp. 643-647.

[8] N. Takato, K. Jinguji, M. Yasu, *et al.*, "Silica-Based Single-Mode Waveguides on Silicon and Their Application to Guided-Wave Optical Interoferometer," *Journal of Lightwave Technology*, Vol. 6, No. 6, 1988, pp. 1003-1010. doi:10.1109/50.4091

[9] Generic Reliability Assurance Requirements for Passive Optical Components, GR-1221-CORE, 1999.