Evaluation of Multimode Optical Waveguides for Optical Bus Interconnects

Alan X. Wang
Oregon State University, Corvallis, OR, 97331

wang@eecs.oregonstate.edu; Phone: (541)-737-4247

ABSTRACT

In this paper, we evaluate the performance of polymer multimode waveguide and metallic hollow core waveguide for complicated board level optical interconnect structures such as optical bus. Numerical simulation suggests that metallic hollow core waveguide with 50μm×50μm dimension can provide acceptable optical propagation loss as low as 0.045dB/cm, less than 0.5dB bending loss per 180 degree turning with 5mm radius, 0.25dB extra splitting loss, and a large tolerance to angular deviation of the micro-mirror coupler. The conclusion is that silver coated metallic hollow core waveguide will be a better choice for board level optical bus than conventional polymer multimode waveguide.

Keywords: Optical interconnects; Optical backplane; Polymer Waveguide; Metallic hollow core waveguide

1. INTRODUCTION

Conventional optical interconnect using point-to-point optical waveguide or waveguide array fails to provide non-congestional interconnection among multiple points, which is due to the intrinsic nature of such architectural topology [1–4]. Such a point-to-point optical interconnect structure is useful to most high performance computer (HPC) system only when it is combined with electrical switch backplanes. This topological deficit critically restricts the gain in the bandwidth capacity, because it cannot carry out multicast/broadcast as effectively as the backplane bus can do [5]. For such hybrid optical-electrical system, besides the hop delay, each data transfer phase inevitably incurs a routing overhead, which makes it rather difficult to minimize the overall interconnect latency. In order to overcome these challenges, we have demonstrated an optical backplane bus that are based on substrate-guided optical interconnects [5–8], which is a direct network to possess very high connectivity. For example, optical centralized shared bus architecture in uniprocessing systems has been experimentally verified by applying it to fulfill the critical microprocessor-to-memory interconnects [6]. However, such substrate-guided optical bus structures have intrinsic drawbacks in packaging density and stability concerns comparing with optical waveguide approaches [8]. A master-slave parallel optical bus was reported based on pellicle beam splitters, but the fabrication processes are not cost-effective [9]. Recently, a polymer waveguide based bidirectional optical bus system with 3-to-3 nodes was designed in Figure 1 [10], which has demonstrated the advantages of enhanced bandwidth, increased reliability, package compatibility and significantly lower fabrication cost. However, the performance of such optical bus interconnect architecture is significantly limited by the optical loss of the complicated polymer multimode waveguide structure consisting of straight waveguides, bending waveguides, micro-mirror couplers, power splitters and combiners.

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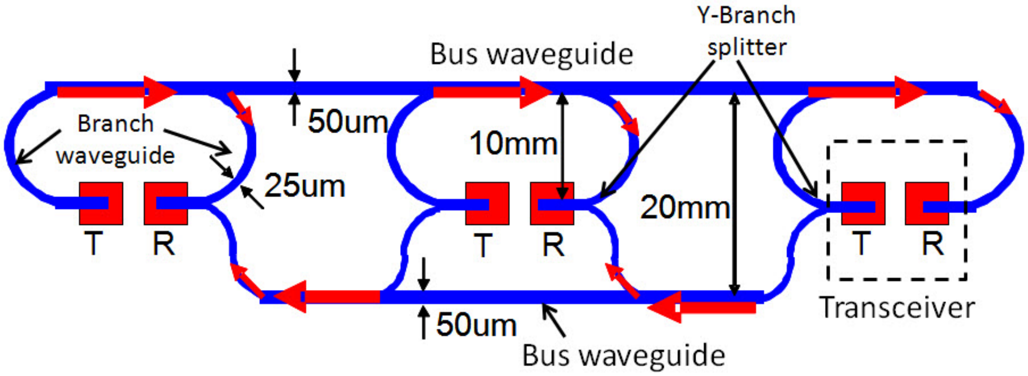

Fig.1 Schematic view of a 3-to-3 optical bus architecture

In this paper, we propose a silver coated metallic hollow core waveguide for the optical bus structure, which numerically compare its performance with conventional polymer multimode waveguide using ray tracing method and beam propagation method.

2. NUMERICAL EVALUATION OF METALLIC HOLLOW CORE WAVEGUIDE AND POLYMER MULTIMODE WAVEGUIDE

Metallic hollow core waveguide is an air-core light pipes with a rectangular cross section with a high-reflectivity metalized coating (usually silver coating for the lowest loss) in the interior. They have several interesting properties that make them ideal candidates for use in intra-board interconnections [11]: (1) low propagation loss <0.05 dB/cm, (2) ease of fabrication, (3) low numerical aperture NA < 0.01, and (4) an effective index of ~1. The unity effective index yields zero skew between waveguide channels and also the lowest latency (0.033ns/cm) per unit length.

2.1 Straight Waveguide

The theoretical loss of the hollow core waveguides was estimated by Marcatili [12] for circular metallic waveguides. For square waveguides whose core dimension a is much larger than the wavelength, the attenuation can be approximated by [13]:

$$\alpha = \frac{\lambda^2}{(2a)^3}\mathrm{Im}\left(\frac{1+n_{\mathrm{clad}}^2}{2\sqrt{1-n_{\mathrm{clad}}^2}}\right) \quad (1)$$

where n_{clad} is the refractive index of the metal cladding layer. From this expression we see that the loss can be made small by choosing the waveguide dimension to be much larger than a wavelength. For silver coated waveguide, as we all know, the refractive index of silver strongly depends on wavelength, as shown in Figure 2 (a). At 850nm wavelength, the refractive index n_{Ag}=0.15+i*5.68. Figure 2 (b) shows the simulated propagation loss of the fundamental mode at the wavelength range from 0.6~1.1μm for metallic hollow core waveguides with cross section of 50μm×50μm, 75μm×75μm, 100μm×100μm, and 150μm×150μm. It is seen that as the waveguide cross section increases, the propagation loss will decrease significantly. For 50μm×50μm multimode waveguide, which is the most widely used dimension for board level optical interconnects, the propagation loss at 850nm wavelength is around -0.045dB/cm. This is comparable with many low loss polymer materials. It is true that for optical bus structure, higher order modes will excited due to the complicate structure, and we will expect the propagation loss can be higher than the theoretical

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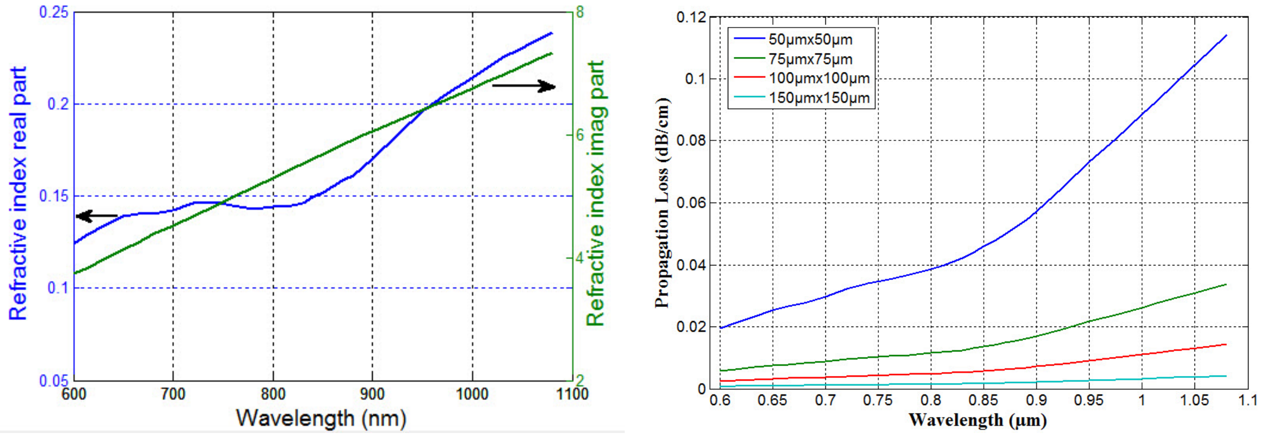
results.

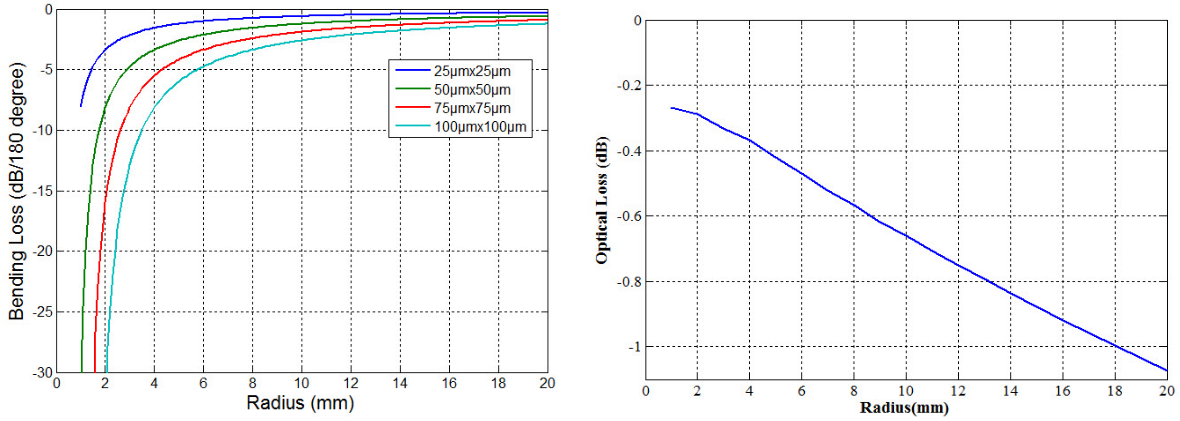


(a) (b)

Fig.2 (a) Refractive index of silver at the wavelength range from 600~1100nm (b) Calculated propagation loss of silver hollow core waveguide for the fundamental mode

2.2 Bending Waveguide

The calculation of bend losses in multimode bent waveguides constitutes a considerable challenge, as modeling approaches used in the case of single-mode waveguides such as bent mode solvers cannot be used. A geometric optics approach was proposed as the most suitable alternative to predicting leakage losses in multimode bent waveguides [14], and is used to calculate the bending loss of polymer waveguide with 180° turning, which is shown Figure 3 (a). At an acceptable bending radius of 5mm, 50μm×50μm waveguide has a bending loss around 3dB. The mechanism of the bending loss of metallic hollow core waveguide is different from multimode polymer waveguide since nearly no light can leakage from the metal waveguide. In bending waveguide, the optical loss will increase majorly due to the increased single-reflection loss and the shorter distance between each reflection, which means there will be more reflections in the bending waveguide than a straight waveguide. Figure 3 (b) shows the simulated bending loss of metallic hollow core waveguide of 50μm×50μm cross section with 180° turning. The bending loss of metallic hollow core waveguide is much smaller than multimode polymer waveguide, especially for small bending radius.



(a) (b)

Fig.3 (a) Bending loss of polymer multimode waveguide; (b) bending loss of metallic hollow core waveguide

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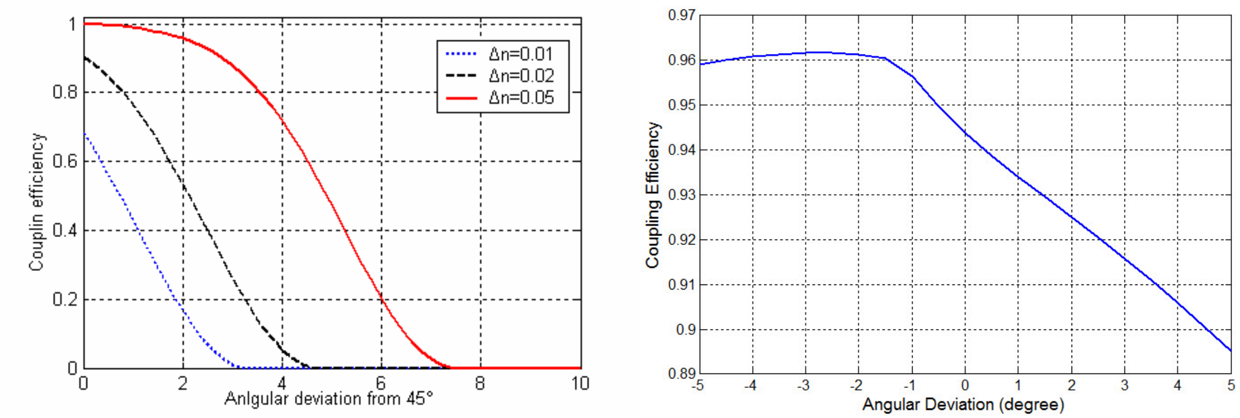
The interesting thing is that smaller bending radius will give lower bending loss, which seems very strange. This is because larger bending radius has longer propagation length, and thus higher absorption. Metallic hollow core waveguide is suitable for ultra-compact bending waveguide down to 1mm.

2.3 Micro-mirror Coupler

The coupling efficiency from the VCSEL to the waveguide can be simulated either by Gaussian beam method or by ray-tracing method. For polymer multimode waveguide, the coupling efficiency strongly depends on the numerical aperture of the waveguide and the angular deviation of the 45° micro-mirror. Figure 4 (a) shows the coupling efficiency of the micro-mirror as a function of the angular deviation for different polymer waveguide. Even for a relatively strong index contrast polymer waveguide (Δn=0.05), it can only tolerate an angular deviation around 4°. For metallic hollow core waveguide, the coupling efficiency is less affected by the angular deviation because of the strong metal reflection. Figure 4 (b) shows the simulated coupling loss as a function of the angular deviation. The maximum coupling efficiency drops from 96% to 89% even with 5°.



(a) (b)

Fig.4 (a) Coupling efficiency of 45° micro-mirror into 50μm×50μm polymer waveguide; (b) Coupling efficiency of 45° micro-mirror into 50μm×50μm metallic hollow core waveguide

2.4 3-dB Power Splitter

The optical loss of the 3-dB power splitter depends on the splitting angle. To avoid extra power loss, the splitting angle is usually controlled below 5°, but with the sacrifice of longer waveguide length. Figure 5 (a) shows the simulated optical loss of the 3-dB power splitter based on polymer multimode waveguide and metallic hollow core waveguide. The input waveguide is 50μm×50μm, and the two branch waveguides after splitting is 25μm×50μm, which is consistence with the publication in [10]. It is seen that metallic hollow core waveguide can provide much lower power loss even with a large splitting angle. For metallic hollow core waveguide, the extra splitting loss is than 0.25dB with splitting angle up to 5°. We realize that there are always fabrication imperfections of optical waveguides. For the 3-dB power splitting, the most important fabrication imperfection comes from the photolithography resolution at the junction region, i.e., the junction where the two waveguides splitting is not a perfect sharp angle. We simulated the optical loss of a 5° 3-dB power splitter at difference photolithography resolution. The interesting phenomenon is that when the photolithography resolution is better than 4.5 μm, metallic hollow core waveguide has a much better performance than polymer multimode waveguide. But when the photolithography resolution keeps

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degrading above 5 µm, the optical loss of metallic hollow core waveguide suddenly increases, and becomes even worse than polymer waveguide. We are still not sure what's the mechanism causing this abnormal loss increase.

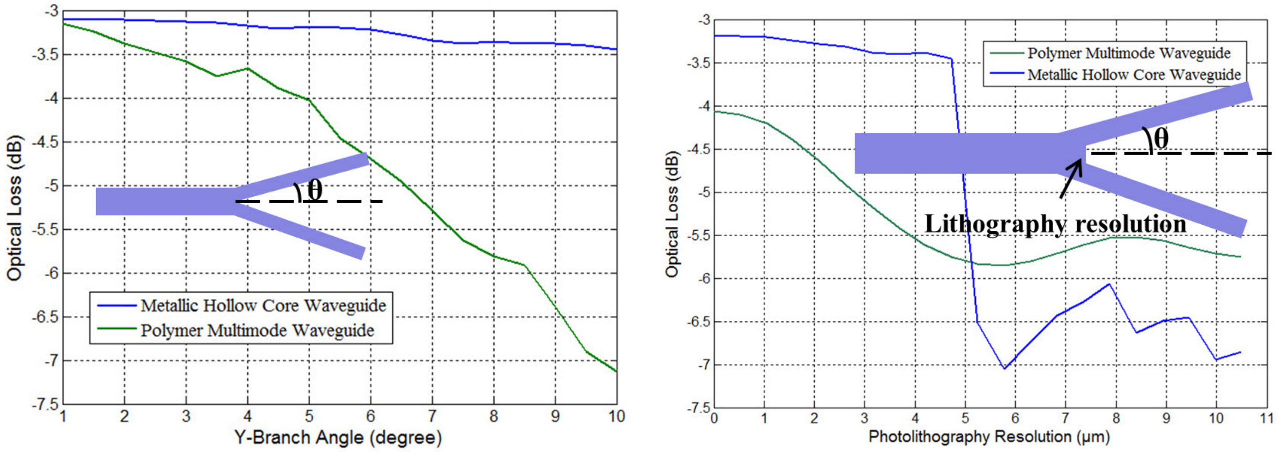

Fig.5 (a) Optical loss of 3-dB power splitter as a function of the Y-branch angle based on metallic hollow core and polymer multimode waveguide; (b) Optical loss as a function of the photolithography resolution

3. CONCLUSION

In summary, we have evaluated the performance of polymer multimode waveguide and metallic hollow core waveguide for board level optical interconnects using optical bus architecture. Numerical simulation suggests that metallic hollow core waveguide with 50µm×50µm dimension can provide acceptable optical propagation loss as low as 0.045dB/cm, less than 0.5dB bending loss per 180° turning with 5mm radius, 0.25dB extra splitting loss, and a large tolerance to angular deviation of the micro-mirror coupler. The conclusion is that silver coated metallic hollow core waveguide will be a better choice for board level optical bus than conventional polymer multimode waveguide.

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