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Right choice for optical bus interconnect: metallic-hollow-core-waveguides or multimode polymer waveguides?

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Abstract. The performance of metallic-hollow-core-waveguides (MHCWs) and multimode polymer waveguides (MMPWs) are numerically evaluated using ray-tracing method for complex board level optical interconnects systems such as optical bus. Based on an ideal model neglecting the waveguide surface roughness, we find that MHCWs will provide lower optical loss for small curvature bending waveguides, 45 deg micro-mirror couplers and optical beam splitters, while MMPWs shows a better optical transmission for straight waveguides. The conclusion is that MHCWs will be a better choice than MMPWs for complex optical bus architectures in terms of performance, cost and stability. *© 2012 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.OE.51.7.075401]

Subject terms: optical interconnects; optical backplane; optical waveguide; ray tracing method.

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1 Introduction

Board-level optical interconnect[1–4] is widely agreed as an essential solution for electric interconnect bottleneck that has constrained high performance computer (HPC) systems and high speed communication modules for many years. However, conventional optical interconnect architecture using point-to-point (P2P) optical waveguide or waveguide array fails to provide noncongestional interconnection among multiple computation nodes, which are extremely important to multiple-core processors and blade servers. As a result, these P2P interconnect architectures developed over the past years will be useful only when they are 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 optical backplanes can do,[5] as it introduces hop delay, routing overhead and interconnect latency. In order to overcome this challenge, optical backplanes using bus architecture that are based on substrate-guided optical interconnects[6–8] are developed. Unfortunately, such substrate-guided optical bus structures have intrinsic drawbacks in packaging density and stability concerns comparing with optical waveguide approaches. Recently, we have designed and experimentally demonstrated multimode polymer waveguide (MMPW) based bidirectional optical bus system that can provide non-congestional interconnection among multiple nodes.[9] As Fig. 1 shows, the structure consists of two parallel optical bus waveguides, which can transmit optical signals from each laser diode (LD) along two opposite directions. The photodetector (PD) of each node is also capable of receiving optical signals from both of these two bus waveguides using two unidirectional branch waveguides that are connected with the bus waveguides. The intra-plane interconnection, i.e., from the LDs or PDs to the optical waveguides, are established through 45 deg micro-mirrors and Y-branch beam splitters. Such optical bus has the advantages of enhanced bandwidth, increased reliability, package compatibility and significantly lower fabrication cost. However, it suffers significantly higher optical loss that is associated with the complex MMPW structure. For example, there are extra optical losses from the bending waveguides and the beam splitters.

In recent years, Tan et al.,[10] from Hewlett Packard have demonstrated an optical multidrop bus using silver coated hollow core waveguides. Such simple optical bus architecture only requires a group of parallel straight waveguides, and uses collimated optical beams for ultra-low loss optical transmission (<0.05 dB/cm). However, it has to use pellicle beam splitters to drop the optical signals, which is difficult to scale to volume production. Although the propagation loss of the fundamental mode of silver coated metallic hollow core waveguides (MHCWs) are theoretically calculated in,[10] analysis of the actual laser beam in the straight waveguide is unexplored, neither in other waveguide structures such as bending waveguide, optical beam splitters and micro-mirror couplers. In this paper, we numerically compare the optical losses of silver coated MHCWs and MMPWs using ray tracing method (RTM). Since the optical scattering loss is proportional to σ^2/d^4, where σ is the surface roughness and d is the waveguide dimension,[11] the optical scattering loss of multimode waveguide is negligible as the waveguide dimension is relatively large and the surface roughness can be significantly reduced with etch-less fabrication processes.[10,12] Given the most recent experimental progress, we use an ideal waveguide model without surface roughness to evaluate the optical loss induced by metal absorption at the air/metal interfaces of MHCWs and the leakage rays of MMPWs. Different waveguide structures including straight waveguides, bending waveguides, 3-dB beam splitters and 45 deg micro-mirrors are compared. The simulation results indicate that the right choice for complex optical bus

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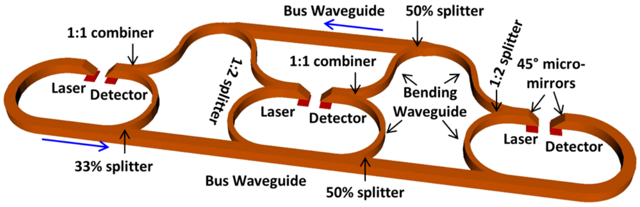

Fig. 1 Schematic view of a 3-to-3 optical bus architecture. The system consists of two parallel bus waveguides and several branching waveguides connected to three nodes (laser diode/photo-detector). The splitting ratio of the power splitters and waveguide couplers are designed to evenly distribute the optical power into each node. 45 deg micro-mirror couplers are used to surface-normally couple light into/out of each node.

interconnects is MHCWs that can provide better performance, lower cost and better stability.

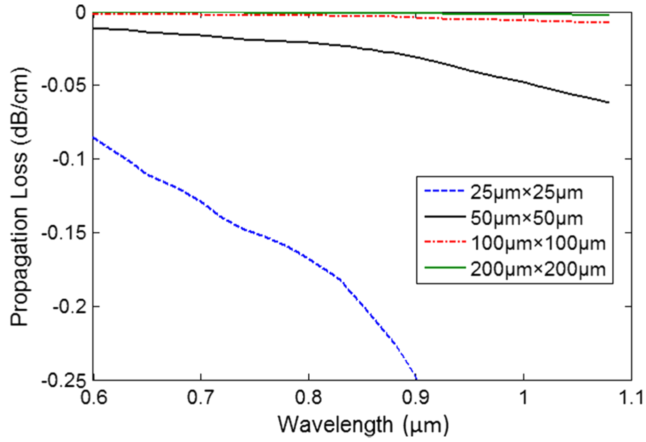

Fig. 2 Propagation loss of MHCWs calculated by electromagnetic (EM) wave absorption.

2 Numerical Evaluation Using RTM

MHCWs are air-core light pipes with rectangular or square cross sections with highly reflective metalized coatings (usually silver coating for the lowest loss) in the interior surfaces. They have several interesting properties that make them ideal candidates for intra-board interconnections: (1) low propagation loss, especially for the fundamental mode which has large incident angles and less reflections with the interfaces, (2) easy fabrication with low cost, (3) strong optical confinement inside the waveguide even with very small curvatures, and (4) an effective index of ∼1, which induces much lower latency than polymer waveguides do. As we all know, the refractive index of silver has a strong dispersion depending on the wavelength.[13] At 850 nm, the refractive index $n_{\mathrm{Ag}} = 0.15 + i * 5.68$. For square cross section MHCWs, whose core dimension a is much larger than the wavelength, the theoretical attenuation of the fundamental mode can be approximated by:[14,15]

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

Figure 2 shows the simulated propagation loss of the fundamental mode at the wavelength range from $0.6 \sim 1.1\ \mu$m for MHCWs with cross sections of $25 \times 25\ \mu\mathrm{m}^2$, $50 \times 50\ \mu\mathrm{m}^2$, $100 \times 100\ \mu\mathrm{m}^2$, and $200 \times 200\ \mu\mathrm{m}^2$. For a typical $50 \times 50\ \mu\mathrm{m}^2$ waveguide at 850 nm, the propagation loss is around 0.03 dB/cm. From Eq. (1), we can see that the propagation loss is inversely proportional to the third power of a. The reason that the optical loss decreases so rapidly is that large waveguide dimension a not only increases the optical path L between interface reflections (the relation between a and L is similar to that of d and L in Fig. 3), but also enlarge the incident angle of the fundamental mode, which is highly effective in reducing the optical loss.

From the above simulation, we can conclude that the optical loss of the fundamental mode of MHCWs is comparable to state-of-the-arts low loss MMPWs.[3,12] However, in real optical interconnect systems, higher order modes will always be excited due to the divergent angle of the incident light, the complex waveguide structures such as bending waveguides and beam splitters, and even the waveguide surface roughness. Considering that the large cross section of the MHCWs

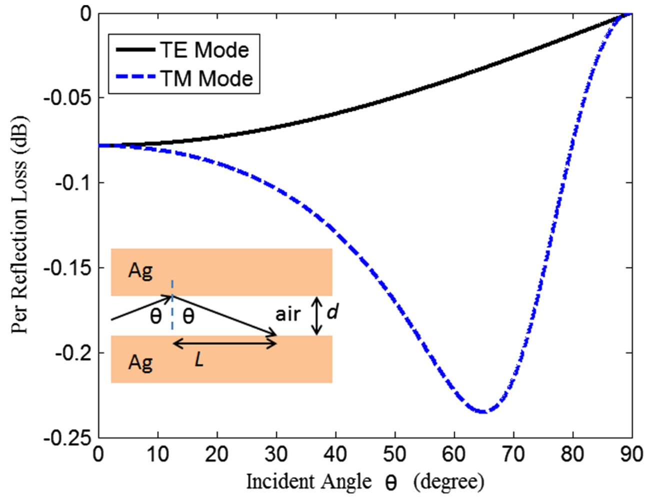

Fig. 3 Optical reflection loss at the air/silver interfaces calculated by Snell's law.

will support a vast amount of guided modes with nearly continuous propagation constants, we can use RTM to model the optical waveguide loss. Using Snell's law, we can calculate the optical loss per reflection for the transverse electric (TE) and transvers magnetic (TM) field at the air/silver interface as a function of the incident angle for a planar waveguide structure, which is shown in Fig. 3. If we do not consider the air absorption, the propagation loss (PL) can be easily obtained as: $\mathrm{PL} = \text{per reflection loss}/L$, where L is the length of optical path along the light direction between two interface reflections, and $L = d \times \tan\theta$ as shown in the inset picture of Fig. 3. To reduce the optical waveguide loss, we can either increase the incident angle or increase the width d of the planar waveguide.

For a large square cross section MHCWs, the difference between the TE and TM mode will disappear due to geometric symmetry. In our simulation, the light source is assumed to be a point source with a Gaussian angular distribution in the x-y plane and is propagating along the z direction:

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$$I(\theta_x, \theta_y) = I_0 \exp\left\{-2\left[\left(\frac{\theta_x}{\alpha_x}\right)^2 + \left(\frac{\theta_y}{\alpha_y}\right)^2\right]\right\}, \tag{2}$$

where α_x and α_y is the divergent angle along the x and y direction, respectively, and θ_x and θ_y is the spatial angle with respect to the light source. To ensure a good coupling, the light source is placed in the center of the beginning surface of the MHCWs and MMPWs. The wavelength of the light source is fixed at 850 nm.

2.1 *Straight Waveguides*

Assuming the incident beam is spatial symmetric ($\alpha_x = \alpha_y$), the propagation loss for different cross section MHCWs as a function of the incident beam divergent angle is plotted in Fig. 4(a). Compared with the propagation loss of the fundamental modes as calculated in Fig. 2, a typical Gaussian beam from a laser diode will suffer a much higher loss. For example, the propagation loss of the $50 \times 50\ \mu\text{m}^2$ MHCWs for a 5 deg Gaussian beam is 0.8 dB/cm, which is much higher than the 0.03 dB/cm value of the fundamental mode. However, if the incident beam is collimated with a small divergent angle of 1 deg, it will only excite the fundamental mode. The RTM simulation in Fig. 4 gives a propagation loss of 0.039 dB/cm. This value is very close to the results from the electromagnetic wave model of 0.03 dB/cm given by Eq. (1). To further confirm the validity of our simulation, we use Rsoft FemSIM to simulate the fundamental mode of MHCWs. Figure 4(b) shows the electric field distribution of the fundamental mode of the $50 \times 50\ \mu\text{m}^2$ MHCW and the calculated effective index of $n_{\text{eff}} = 0.999925 + j * 6.5 \times 10^{-8}$, which corresponds to a beam divergent angle of 0.7 deg and propagation loss of 0.042 dB/cm. Again, this matches the RTM simulation of 0.039 dB/cm very well. For MMPWs, the propagation loss of the straight waveguide is relatively independent of the waveguide cross section if we do not consider the surface roughness. The state-of-the-art results are in the range of 0.01 to 0.1 dB/cm at 850 nm.[3,12] We can conclude that for straight waveguide, MHCWs usually have larger propagation loss than MMPWs. To compete with MMPWs, the incident light needs to be collimated, or the dimension of the cross section has to increase.

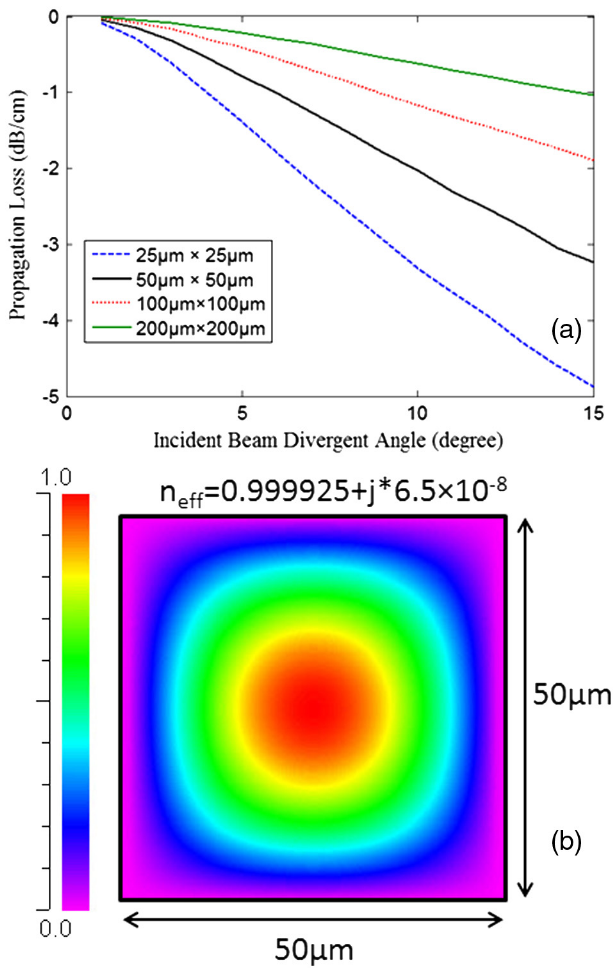

Fig. 4 (a) Propagation of MHCWs as a function of the incident beam divergent angle; (b) fundamental mode of the $50 \times 50\ \mu\text{m}^2$ MHCW by FemSIM simulation.

2.2 *Bending Waveguides*

The propagation loss of bending waveguide has been thoroughly studied in single mode waveguides.[16] Multimode waveguides with a higher refractive index polymer core surrounded by a lower refractive index polymer cladding tend to be much more complex due to the modal coupling. I. Papakonstantinou, et al.,[17] studied the bending loss of MMPWs using beam propagation method (BPM) and experimentally confirmed that the bending losses of MMPWs not only depend on the bending radii, but also on the size of the waveguide cross section. For MHCWs, some early work has been done by E. A. J. Marcatili and R. A. Schmeltzer to study the bending loss of the fundamental mode for long distance communication.[15] However, there have been no reports on how to calculate the bending losses of MHCWs with mixed guided modes for short distance interconnect. In this paper, we use RTM to numerically compare the bending losses of MHCWs and MMPWs. In our modeling, both waveguides have cross sections of $50 \times 50\ \mu\text{m}^2$, 180 deg bending angles regardless of the bending radii, and smooth side walls. As the calculation in Fig. 5 shows, the bending losses will certainly depend on the divergent angle of the incident beam. However, considering the small bending radii (usually <2 cm) for board

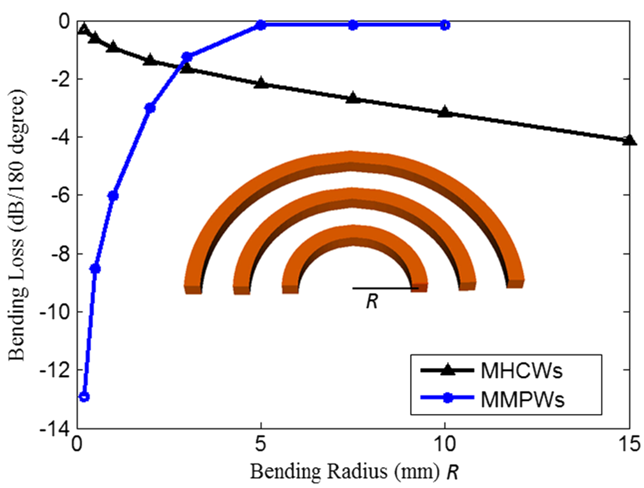

Fig. 5 Bending loss of MHCWs and MMPWs as a function of the bending radius.

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level optical interconnects, the fundamental mode will always be coupled into high order modes at the bending waveguide. The significance of the divergent angle of the incident beam will decrease. In our simulation, the divergent angle is fixed at 5 deg. For MMPWs, the refractive indices of the core and the cladding are 1.47 and 1.45, respectively. Figure 5 shows simulated bending losses of MHCWs and MMPWs that demonstrate completely different trends with respect to the bending radius. For MMPWs, there is a critical bending radius around 5 mm, below which the bending loss starts to increase rapidly. The bending losses of MHCWs are more complex to understand. On one hand, as the bending radius decreases, the incident angle to the metal/air interface will decrease, and the number of interface reflections will increase. Both of these variations will introduce higher propagation loss/length. On the other hand, smaller bending radius will significantly reduce the optical waveguide length for each 180 deg bending, which is indeed much more dominant in determining the total bending loss. As the overall effect, the propagation loss/180 deg bending for MHCWs will actually decrease as the bending radius shrinks. The simulation results in Fig. 5 shows that the cross point between MHCWs and MMPWs is at $R = 3$ mm. As a conclusion, MHCWs will be much more superior to MMPWs for ultra-compact bending (e.g., $R < 1$ mm) waveguide, which is extremely useful for high density optical interconnect systems.

2.3 *Beam Splitters*

The optical losses of beam splitters strongly depend on the splitting angle. To avoid extra power loss at the junction region, the splitting angle is usually set at relatively low values (e.g., <2 deg for MMPWs). The drawback of small splitting angles is that long waveguides are required to separate the beams. Figure 6 shows the simulated optical loss of the 3-dB beam splitter using MHCWs and MMPWs. The input waveguide is $50 \times 50\ \mu\text{m}^2$, and the two branch waveguides after splitting is $25 \times 50\ \mu\text{m}^2$, which is consistence with the waveguide structure used in Ref. 9. The refractive indices of the MMPW core and the cladding are 1.47 and 1.45, respectively. When the splitting angle is very small ($\sim$1 deg), both MHCW and MMPW beam splitters have very small optical losses that are close to the theoretical 3-dB value. With the splitting angle increase, both beam splitters suffer higher optical losses. However, the loss mechanism is different, and hence the sensitivity of the optical loss to the splitting angle varies significantly. For MMPWs, the extra splitting loss comes from the ray leakage at the junction area. With the increase of the splitting angle, more rays exceed the critical angle of total internal reflection, and radiate into the cladding area. For MHCW beam splitter, the silver coating provides a high reflectivity and effectively prevents ray leakage. However, the optical losses still gradually increase because larger splitting angle will reduce the incident angle of the beams after the junction region, which can lead to higher reflection losses. Our numerical comparison shows that MHCW beam splitters are much less sensitive to the splitting angles than the MMPW splitters are. For MHCW beam splitters, the extra splitting loss is less than 0.5 dB with branch angles up to 10 deg.

2.4 *Micro-Mirror Coupler*

The coupling efficiency of 45 deg micro-mirrors on MMPWs have been thoroughly investigated in Refs. 3 and 18. Due to the small index contrast between the core and cladding, a highly reflective metal coating layer must be deposited on the 45 deg surfaces of the polymer waveguides. In principle, 45 deg micro-mirror couplers in MMPWs and MHCWs should offer similar reflectivity. The difference between these two micro-mirror couplers actually comes from the numerical apertures of the waveguides and the tolerance to fabrication variations. If the angle of the micro-mirror deviates from 45 deg, MMPWs will suffer a very high coupling loss because of the smaller numerical aperture. Most of the rays will leak out of the polymer waveguide due to such angular deviation. While for MHCWs, the extraordinary optical confinement will prevent rays from leakage. However, the coupling loss will gradually increase because of the increased propagation loss (smaller incident angle) and the coupling loss with the photodetector with finite surface area. In our simulation, we still use a 5 deg Gaussian beam. The LD and PD are placed 125 μm away from the waveguide layer. The area of the PD is $100 \times 100\ \mu\text{m}^2$. To minimize the effect of propagation loss, the waveguide length is set at 1 mm, and the micro-mirrors at both ends are assumed to have the same angle. To ensure light can

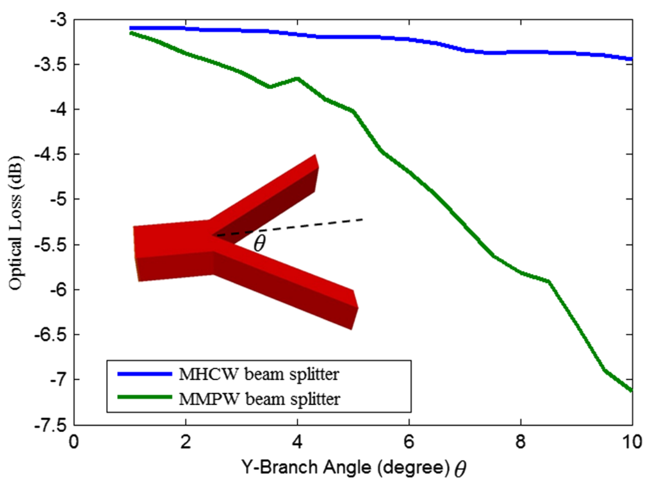

Fig. 6 Optical loss of beam splitters using MHCWs and MMPWs.

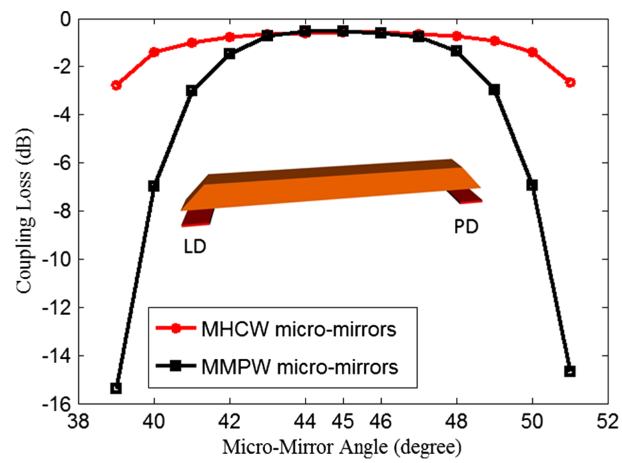

Fig. 7 Coupling loss as a function of the micro-mirror angle for MHCWs and MMPWs.

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freely couple into and out of the MHCW, transparent windows with 100 μm length are opened under the 45 deg micro-mirrors. Figure 7 shows the simulated micro-mirror coupling losses as a function of the mirror angle for MHCWs and MMPWs. For MMPWs, the micro-mirrors can only tolerate about ± 3 deg angular deviation for 2 dB coupling loss, while for MHCWs, the micro-mirrors can have a large fabrication tolerance of ± 5 deg. One comment we need to point-out is that most of the optical coupling loss actually comes from the first micro-mirror for both MMPWs and MHCWs. The optical coupling loss of the end micro-mirror is negligible as long as the photodetector is relatively close to the waveguide and its detecting area is large enough comparing with the waveguide dimension.

3 Conclusion

In conclusion, we have used RTM to numerically compare the optical losses of MHCWs and MMPWs. For straight waveguide, MHCWs can provide similar propagation loss with MMPWs only when the incident light is collimated to excite the fundamental mode. For complex waveguide structures, MHCWs show significant advantages over MMPWs that they can reduce the bending loss and beam splitting loss, and tolerate a larger fabrication error to the 45 deg micro-mirror couplers. Considering that MHCWs can be fabricated by similar processes as those for MMPWs, and MHCWs only require cheap and robust polymer materials such as Su-8, MHCWs are expected to achieve significant advantages over MMPWs for complex optical bus interconnects in terms of performance, cost and stability.

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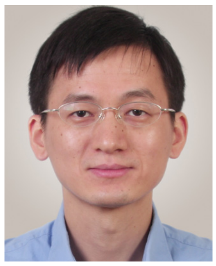

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