

3D Photonic Integration: Cascaded 1x1 3D Multi-mode Interference Couplers for Vertical Multi-layer Connections

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ABSTRACT

A vertical interconnection across four stacked polymer waveguide layers using 3D multi-mode interference couplers (3D MMIs) is presented. This system bridges a vertical distance of 21.6 μm with a minimum on-chip loss of 2.5 dB. The multi-layer connection is a basic element for novel applications, like large-scale optical switching matrices with a waveguide crossing-free architecture and a small footprint.

Keywords: 3D photonic integration, polymer waveguide, multi-layer waveguide system, vertical multi-mode interference coupler.

1. INTRODUCTION

By extending planar photonic integrated circuits (PICs) into the 3rd dimension, a new degree of freedom in their design arises. This leads to novel applications such as waveguide crossing-free large-scale switching matrices, multicore-fiber-PIC-interconnections and 3D optical phased arrays. Especially with regard to complex crossing-free optical switches, passive routing (Figure 1 (b)) over more than two layers is necessary for a small footprint. The crossing-free routing in Figure 1 is enabled by a multi-layer waveguide system for multiple parallel optical flows and vertical interconnects consisting of 1x1 3D MMIs [1]. 3D PICs with only two connected waveguide layers have already been demonstrated on HHI's polymer-based photonic integration platform PolyBoard as reported in [1] – [4]. The 1x1 3D MMIs were successfully fabricated with on-chip losses of 1 dB [1] for a vertical distance of 7.2 μm (centre-to-centre).

The polymer waveguide technology allows a reproducible, low-loss fabrication of 1x1 3D MMIs over several layers [1, 5]. Such a multi-layer connection for four waveguide layers is shown in Figure 1 (a). This structure is a basic element for a crossing-free routing, as shown in Figure 1 (b), inside a switching matrix. The light path covers a vertical distance of 21.6 μm . The system exhibits low on-chip losses of 2.5 dB.

Subsequently, the design of the multi-layer vertical interconnects is shown. Furthermore, the results of the characterization of such a fabricated device as shown in Figure 1 (a) are presented.

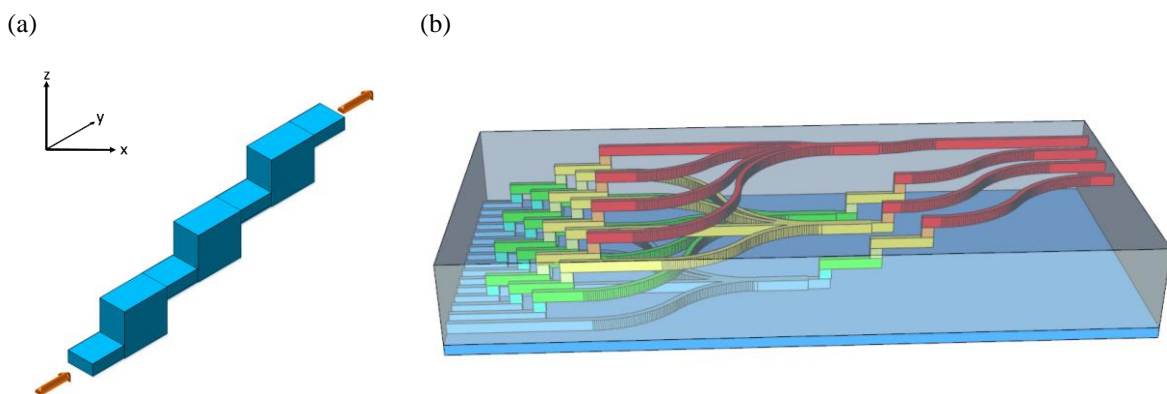


Figure 1: 3D sketch of a multi-layer connection for four waveguide layers (a) and a 3D sketch of a concept of a crossing-free waveguide routing (b) for large-scale optical switching matrices.

2. DESIGN AND SIMULATION

The design to connect four waveguide layers by three cascaded 1x1 3D MMIs is shown in Figure 1 (a). The basic building block is the 1x1 3D MMI in Figure 2 [1]. The single-mode input and output waveguides of a 1x1

3D MMI are connected by a multi-mode interference section. The light is transmitted from the single-mode waveguide with a height of $3.2\ \mu\text{m}$ to a $10.4\ \mu\text{m}$ high MMI section. The waveguides are channel waveguides based on a polymer core and a polymer cladding with an index contrast of $\Delta n = 0.03$ at $1550\ \text{nm}$ [2, 3]. In the MMI, a multi-mode field arises, resulting in self-interference. Based on the self-imaging theory, an image of the input field at the output waveguide is obtained for a fixed combination of length and height [6, 7]. This output field is similar in phase and intensity to the input field.

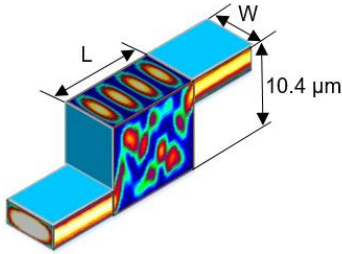


Figure 2: 3D sketch of a vertical 1x1 3D MMI for connecting two vertical waveguide layers. The sketch shows the simulation results of the optical light field [1].

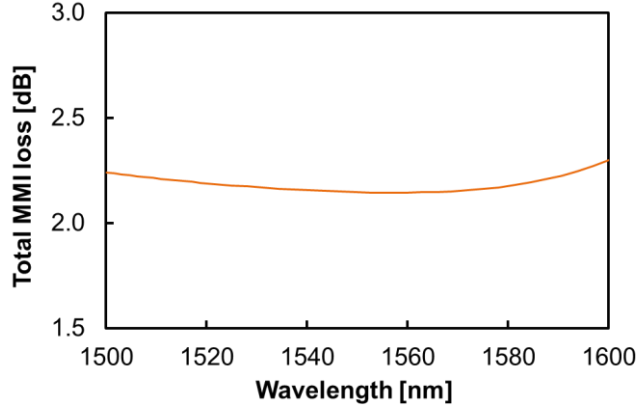


Figure 3: Simulated MMI loss depending on the wavelength of a multi-layer connection for four vertical waveguide layers with fixed parameters of 1x1 3D MMIs (MMI length $L = 173\ \mu\text{m}$, MMI width $W = 1.4\ \mu\text{m}$ and MMI height of $10.4\ \mu\text{m}$).

To determine the expected intensity of the output field as a function of the wavelength, the multi-layer connection structure (Figure 1 (a)) with three connected 1x1 3D MMI was implemented in FIMMPROP. Starting point of the simulation is based on the successfully fabricated and characterized 1x1 3D MMIs with a MMI height of $10.4\ \mu\text{m}$, MMI length $L = 173\ \mu\text{m}$ and MMI width $W = 1.4\ \mu\text{m}$ [1]. In Figure 3 the total MMI losses for three cascaded 1x1 3D MMIs are shown depending on the wavelength for the given parameter set. As a result, the simulation yields a minimum total MMI loss of 2.1 dB at a wavelength of 1550 nm.

3. CHARACTERIZATION

Optical transmission measurements were conducted on a fabricated multi-layer connection of four waveguide layers based on three cascaded 1x1 3D MMIs. Figure 4 shows the wavelength dependent on-chip losses for such a device with a MMI length $L = 173\ \mu\text{m}$, a MMI width $W = 1.4\ \mu\text{m}$ and a MMI height of $10.4\ \mu\text{m}$. The on-chip losses are normalized by the average transmission losses of straight reference waveguides per waveguide layer (approx. 2 dB). Figure 4 shows for the device a minimum on-chip loss of 2.5 dB at a wavelength of 1517 nm. The device was successfully fabricated with low additional loss ($< 0.4\ \text{dB}$) compared to the simulation (Figure 3).

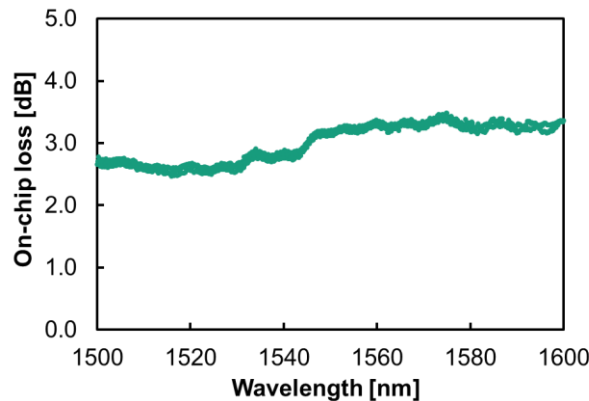


Figure 4: Optical transmission measurement on a multi-layer connection of four vertical waveguide layers consisting of three cascaded 1x1 3D MMIs with a MMI height of $10.4\ \mu\text{m}$, MMI length $L = 173\ \mu\text{m}$ and a MMI width $W = 1.4\ \mu\text{m}$. The losses of the device were normalized by the transmission loss through a straight reference waveguide (2 dB) without vertical interconnection.

Figure 4 shows a shift of the wavelength with the minimum loss compared to the simulation results in Figure 3 to smaller wavelengths. Based on the self-imaging theory, this shift may be due to the variation of the parameters

MMI length or MMI height [6, 7]. For a closer look at the reason, the measurements were repeated on devices with different MMI lengths. Figure 5 shows the on-chip losses over the wavelength for different MMI lengths. It can be seen that for all lengths, regardless greater or smaller than 173 μm , the shift to shorter wavelengths occurs. Hence, the variation of the MMI height is the decisive parameter. Due to the offset to smaller wavelengths, it follows from the self-imaging theory that the MMI height is smaller than 10.4 μm [6, 7]. In Figure 6 the simulation results for different MMI heights for a multi-layer connection over four waveguide layers are shown. From Figure 6 it can be seen that at a MMI height of 9.8 μm , the minimal losses occur at 1518 nm. In comparison to the measurement results in Figure 4, a similarly large wavelength shift is observed. The effective MMI height per 1x1 3D MMI is hence 0.6 μm smaller than assumed. In addition, it can be seen that with a difference of 0.6 dB the measurement results are close to the simulation results. This shows that the height is a sensitive parameter for the wavelength dependence of the device, but does not have a major impact on the minimal losses on this short range.

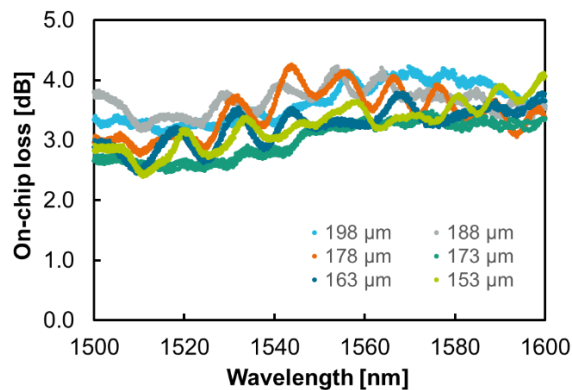


Figure 5: Optical transmission measurements on multi-layer connections of four waveguide layers connected by three 1x1 3D MMIs with a fixed MMI height of 10.4 μm and a MMI width of 1.4 μm . The MMI lengths L varies for the different devices. The losses of the devices were normalized by the transmission loss of straight reference waveguide (2 dB) without vertical interconnection.

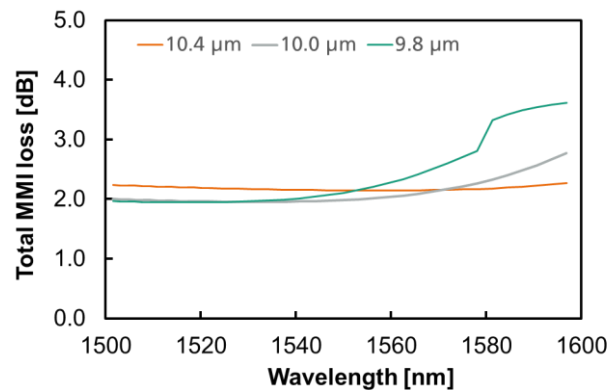


Figure 6: Simulated MMI loss depending on the wavelength of a multi-layer connection for four vertical waveguide layers with fixed MMI length $L = 173 \mu\text{m}$ and MMI width $W = 1.4 \mu\text{m}$ for three different MMI heights: 10.4 μm (orange), 10.0 μm (grey) and 9.8 μm (green).

4. CONCLUSION

A connection of four waveguide layers using three cascaded vertical 1x1 3D MMI couplers with a vertical distance of 21.6 μm was successfully fabricated on the HHI's PolyBoard platform. The multi-layer connection exhibited a minimum on-chip loss of 2.5 dB at a wavelength of 1517 nm. Furthermore, it was shown that the height of the MMI is a critical parameter with regard to the wavelength with the lowest losses. This multi-layer structure is a basic element for novel applications, such as complex waveguide crossing-free routing for optical switching matrices.

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