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.

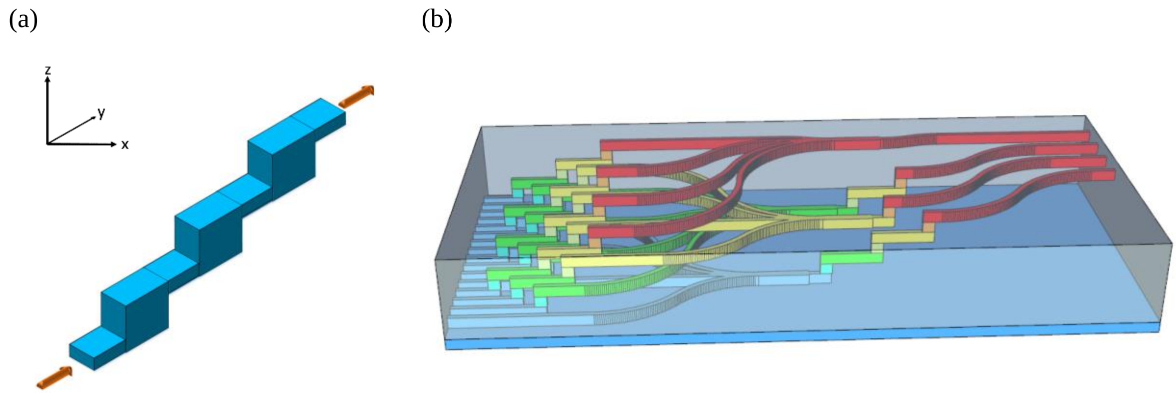

Figure 1: 3D sketch of a multi-layer connection for four waveguide layers (a) and a 3D sketch of a concept of a crossing-free waveguide routing (b) for large-scale optical switching matrices.

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 µm to a 10.4 µm high MMI section. The waveguides are channel waveguides based on a polymer core and a polymer cladding with an index contrast of Δn = 0.03 at 1550 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.

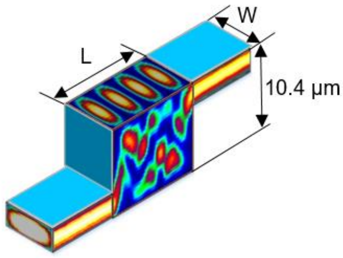

Figure 2: 3D sketch of a vertical 1x1 3D MMI for connecting two vertical waveguide layers. The sketch shows the simulation results of the optical light field [1].

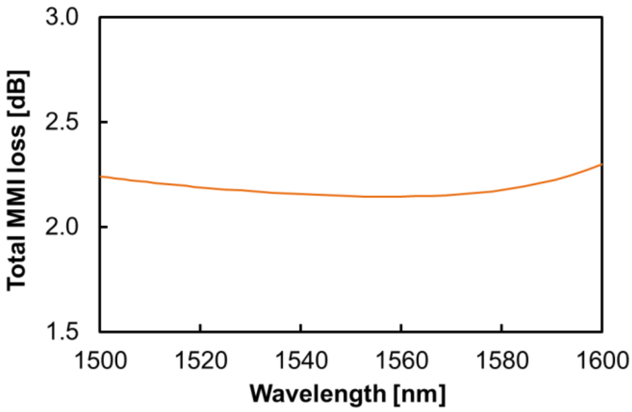

Figure 3: Simulated MMI loss depending on the wavelength of a multi-layer connection for four vertical waveguide layers with fixed parameters of 1x1 3D MMIs (MMI length L = 173 µm, MMI width W = 1.4 µm and MMI height of 10.4 µm).

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 µm, MMI length L = 173 µm and MMI width W = 1.4 µm [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 µm, a MMI width W = 1.4 µm and a MMI height of 10.4 µm. 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 dB) compared to the simulation (Figure 3).

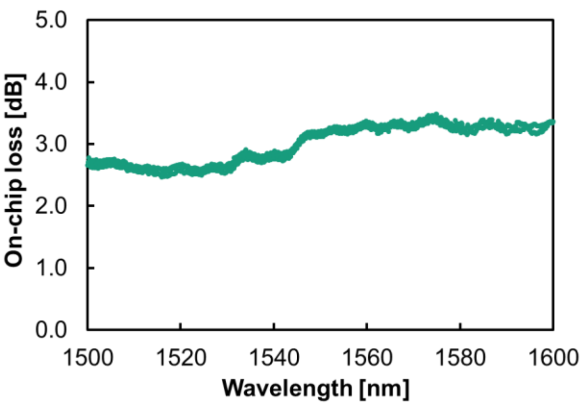

Figure 4: Optical transmission measurement on a multi-layer connection of four vertical waveguide layers consisting of three cascaded 1x1 3D MMIs with a MMI height of 10.4 µm, MMI length L = 173 µm and a MMI width W = 1.4 µm. The losses of the device were normalized by the transmission loss through a 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.

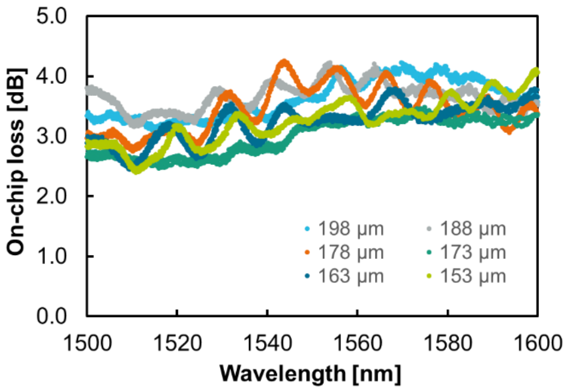

Figure 5: Optical transmission measurements on multi-layer connections of four waveguide layers connected by three 1x1 3D MMIs with a fixed MMI height of 10.4 µm and a MMI width of 1.4 µm. The MMI lengths L varies for the different devices. The losses of the devices were normalized by the transmission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

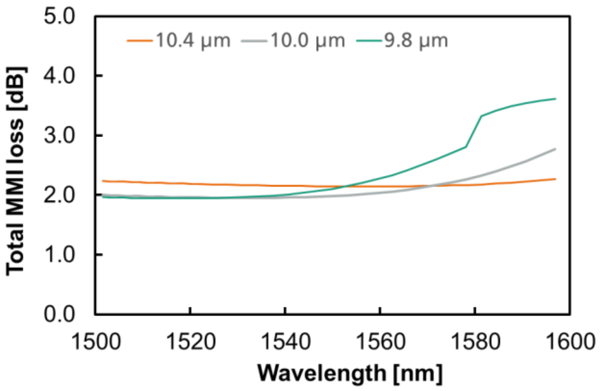

Figure 6: Simulated MMI loss depending on the wavelength of a multi-layer connection for four vertical waveguide layers with fixed MMI length L = 173 µm and MMI width W = 1.4 µm for three different MMI heights: 10.4 µm (orange), 10.0 µm (grey) and 9.8 µm (green).

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.

ACKNOWLEDGEMENTS

This work was partially funded through the project ICT-3PEAT by European Union's Horizon 2020 research and innovation programme under grant agreement No 780502.

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