Low-loss Vertical MMI Coupler for 3D Photonic Integration

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Abstract *A polymer vertical multi-mode interference coupler with device losses below 1.2 dB for a vertical centre-to-centre waveguide distance of 7.2 µm is presented.*

Introduction

Nowadays, photonic integrated circuits (PICs) typically are planar, 2D-like structures. However, novel applications such as multicore-fiber-PIC interconnections or large-scale switching matrices greatly benefit from the additional flexibility introduced by multiple waveguide layers in PICs. To take full advantage of this flexibility, connections between different layers are necessary. There are different approaches to realize such couplers. A vertical coupling can be achieved by means of a pair of micromirrors[1] with an angle of ±45° with respect to the optical axis, vertical waveguide bends[2], or a vertical MMI coupler structure as an interconnection between two polymer-waveguide layers, still with losses higher than 3 dB[3].

In this work, we present a polymer vertical MMI coupler[3] (VMC) based on HHI's PolyBoard photonic integrated platform[4-6]. First, the design and numerical simulation results are shown. Additionally, the technology processes were optimized for the fabrication of vertical MMI couplers. This yielded on chip losses lower than 1.2 dB at a wavelength of 1550 nm for a connection of two waveguide layers with a vertical centre-to-centre distance of 7.2 µm.

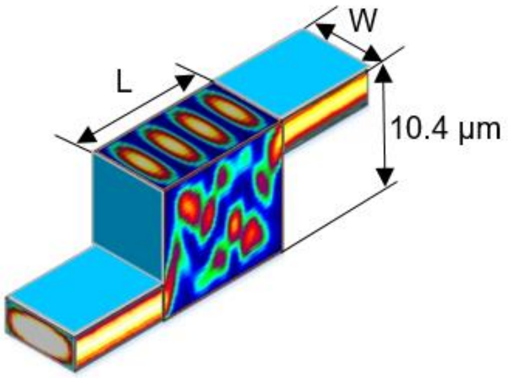

Fig. 1: 3D sketch of a vertical MMI coupler for a height of 10.4 µm with simulation results for the optical light field.

Design and Simulation

The design of a vertical interconnection between two waveguide layers resembles a standard planar 1x1 multi-mode interference coupler (MMI), which is rotated 90° along the longitudinal axis. Fig. 1 shows a 3D schematic of such a vertical MMI coupler[3]. The structure consists of an input single-mode waveguide in the lower layer, the interconnection multi-mode section, and a single-mode output waveguide in the upper layer (longitudinal section on Fig. 2). The refractive index contrast between waveguide material and cladding is Δn = 0.03, ensuring a single-mode operation of the waveguides a height of 3.2 µm. In the 10.4 µm high interconnecting waveguide section, a multi-mode field excited by the self-interference of the single-mode input arises[7]. Based on the self-imaging theory of MMIs[7,8] there exists a combination of length and width of the multi-mode area where an image arises at the output, that is similar in intensity and phase to the entrance mode field.

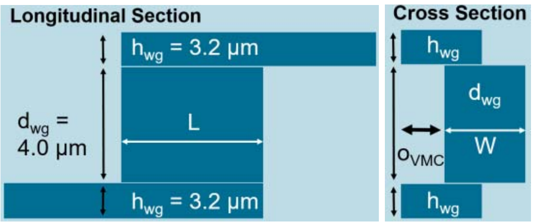

Fig. 2: Schematic of the longitudinal section of the vertical coupler with three waveguide layers (left), and of the cross section of a vertical MMI coupler indicating a possible offset in the fabrication (right).

The complete structure was implemented in FIMMWAVE. The MMI length *L* and width *W* were optimized numerically at a wavelength of λ = 1550 nm (Fig. 3). The minimum loss is 0.8 dB for a width of 1.4 µm at lengths between 170 µm to 180 µm.

Due to process tolerances during wafer fabrication, an offset between the individual layers of the vertical MMI coupler[3] may occur, as illustrated in Fig. 2. Hence, one goal of the numerical investigations is to quantify the fabrication tolerances for the given set of parameters. Fig. 4 shows the simulation results of three different combinations of MMI width and

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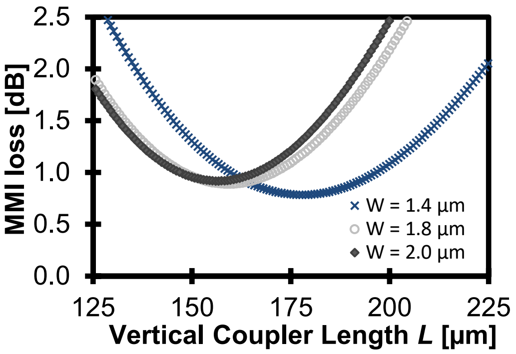

Fig. 3: Simulated loss at 1550 nm as a function of the vertical MMI coupler length for different widths (1.4 µm, 1.8 µm and 2.0 µm).

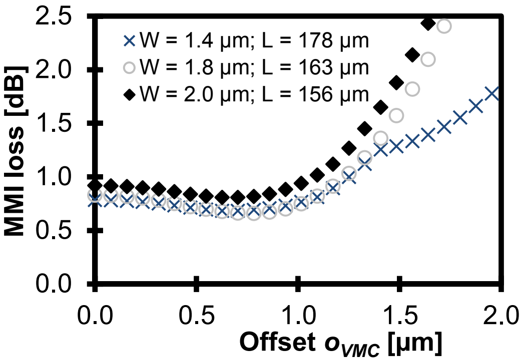

Fig. 4: Simulated loss at 1550 nm as a function of the offset for the combinations of widths and lengths of *W* = 1.4 µm and *L* = 178 µm, *W* = 1.8 µm and *L* = 163 µm, *W* = 2.0 µm and *L* = 156 µm.

length (W = 1.4 µm and L = 178 µm, W = 1.8 µm and L = 163 µm W = 2.0 µm and L = 156 µm). The highest offset tolerances occur at a width of 1.4 µm. The offset o_{VMC} between the waveguide layers, shown in Fig. 2 (cross section), induces two interfaces in the middle section d_{wg} of the vertical MMI coupler. At an offset of approx. 0.6 µm, the interfaces are arranged in order that the light from the middle section is reflected in the top waveguide. Hence, the MMI loss decreases for an offset range of 0.4 µm to 0.6 µm (Fig. 4).

Technology and Fabrication process

The waveguide and cladding layers comprise of the ZPU-12 material series of ChemOptics Inc.[9], and are fabricated using a spin-coating process, followed by UV curing. The waveguide layers are structured by standard UV-photolithography and oxygen plasma reactive ion etching. The layer deposition alternates between waveguide and cladding material[3]. To realize the interconnection between the waveguide layers, a thinning of the second cladding layer down to the top edge of the lower waveguide layer is required[3]. In this standard process, the titanium mask (Ti-Mask) was removed directly after the waveguide layer structuring. In a second attempt, we introduced an optimized process in order to achieve a higher precision in the layer thickness: Different from the standard process, we left the Ti-Mask in place after waveguide structuring. This enabled an easier and more precise measurement of the cladding layer thickness over the top edge of the waveguide layer and acts as an etch stop during the etching of the second cladding layer. After reaching the top edge of the waveguide layer, the Ti-Mask was removed.

The optimized process was used for fabrication of vertical MMI couplers on 4-inch wafer scale. The cross sections in Fig. 5 demonstrate the precision of the fabrication process. The offset between the layers is minimal and below the measurement accuracy of the microscope. Furthermore, the height of the coupler section matches the designed value. A slight deviation is visible in the waveguide layer heights, where the top layer is too high (3.8 µm). However, as the increased thickness is not expected to give rise to significant higher order modes, the device performance is not expected to deteriorate.

Characterization

Optical transmission measurements were conducted on the fabricated structures, and

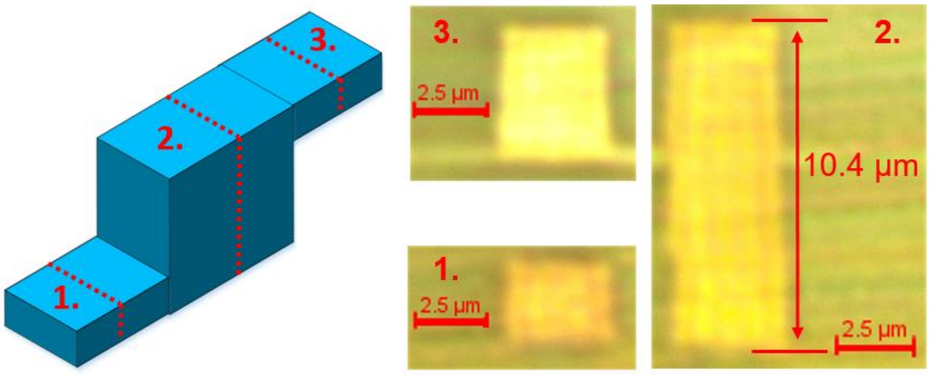

Fig. 5: Three cross section pictures from the fabricated vertical MMI coupler. The 3D sketch on the left side outlines the position of the cross section pictures in the device.

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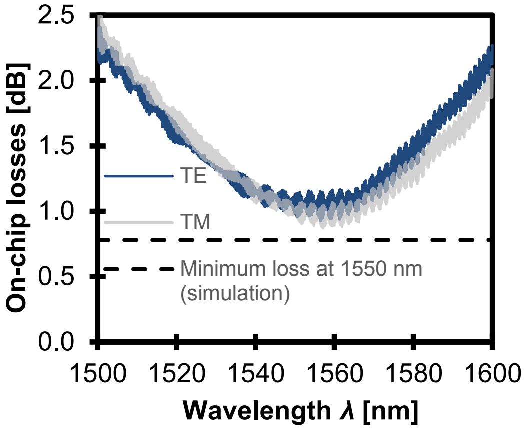

Fig. 6: Results from the fiber-chip-fiber measurement of a vertical MMI coupler for TE and TM polarizations. The measured vertical MMI coupler have a length of 173 µm and a width of 1.4 µm. The marked line corresponds to the simulated minimum loss for a vertical MMI coupler width of 1.4 µm and a wavelength of 1550 nm.

normalized by the transmission loss through a straight reference waveguide (0.9 dB) without vertical interconnection. The wavelength-dependent on-chip loss through a vertical MMI, is shown in Fig. 6. It features minimal losses of approx. 1.0 dB for the TE and 0.9 dB for the TM polarization at a wavelength of 1557 nm, close to the 0.8 dB loss predicted from simulations.

The shift relative to the design wavelength of 1550 nm can be compensated by reducing the coupler lengths in future device iterations.

The achieved loss of the vertical MMI coupler fabricated with the optimized process is about 2 dB lower than previously published work[3] on such structures. The low on-chip loss of the newly designed vertical MMI couplers enables their use in novel 3D PICs.

Conclusions

The vertical MMI coupler on the HHI's PolyBoard platform were designed and successfully fabricated, showing an on-chip loss of approx. 1.0 dB at 1557 nm. The optimized fabrication process yielded a higher precision in the layer thickness and a negligible lateral layer offset. This work paves the way towards the development of 3-dimensional PICs with efficient interlayer coupling of the light. This enables, among others, the design of large-scale switching matrices without waveguide crossing (Fig. 7 a)), 3D optical phased arrays for LIDAR applications, and the interconnection of few-mode and multi-core fibers (Fig. 7 b)), with classical planar PICs.

Acknowledgements

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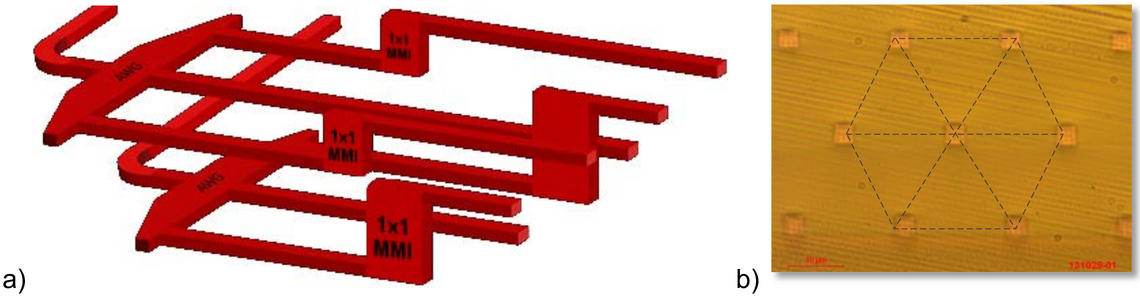

Fig. 7: a) 3D sketch of a multilayer system for switching and sensing modules with vertical MMI couplers. b) Cross section picture of multilayer polymer waveguides. The gap and arrangement of the waveguide position can be adapted to different types of multicore fibers.

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