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1x4 Vertical Power Splitter/Combiner: A Basic Building Block for Complex 3D Waveguide Routing Networks

(Student paper)

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A novel polymer-based 1x4 vertical multimode interference (MMI) coupler for 3D photonics is presented. It connects four vertically stacked waveguide layers with a spacing of 21.6 µm (center-to-center). The functionality is demonstrated on a fabricated device.
Keywords: *3D photonic integration, polymer-based platform, multi-mode interference coupler*

INTRODUCTION

Introducing a new level of design freedom through 3D integration in photonic integrated circuits (PICs) requires the development of new 3D basic building blocks. Application areas for 3D PICs are large-scale optical switching matrices and optical beam forming networks for 2D beam steering in LIDAR and wireless optical communication. These applications benefit from crossing-free waveguide routing, thus reduced crosstalk, and significantly increased design flexibility through 3D photonics. In this work, a new basic building block, a 1x4 3D MMI (Fig. 1), is presented for the first time. The starting point for the development of the 1x4 3D MMI is the well-known planar 1x4 MMI [1]. In addition, 3D waveguide networks have already been successfully demonstrated in the hybrid integration platform PolyBoard [2, 3] and first vertical 3D MMIs have been realized on this platform as well [4]. So far, this has been limited to direct connections between two vertical stacked waveguide layers. A component frequently used for this purpose is the 1x1 3D MMI, which was also used to connect four waveguide layers in cascaded form [5]. The novel 3D MMI coupler proposed in this work directly connects four vertically stacked waveguide layers for the first time and allows to fabricate switching matrices with a small footprint and to realize 3D optical phased arrays with four vertically stacked waveguide layers showing the necessary uniformly distributed light intensity.

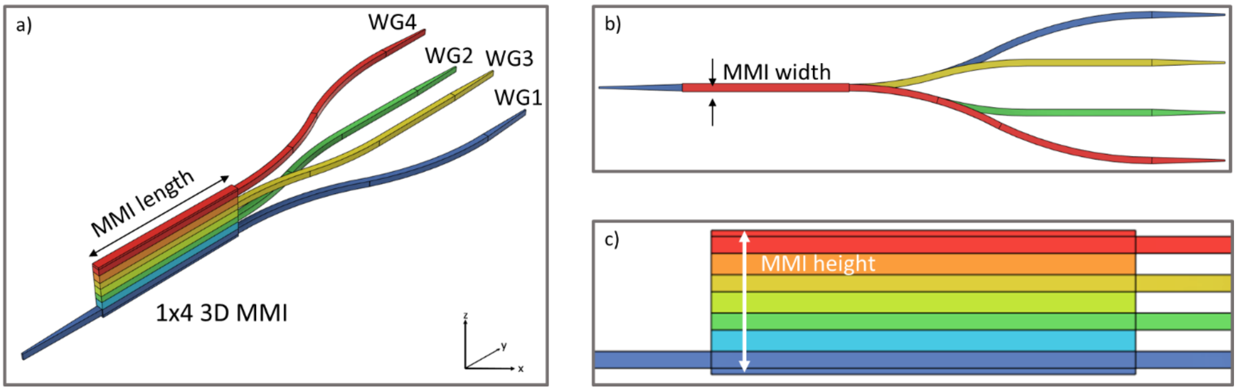

Fig. 1: Design of the 1x4 3D MMI to connect four vertically stacked waveguide layers. The 3D illustration a) includes the nomenclature of the output waveguides. The 1x4 3D MMI is shown schematically in (b) top view and in (c) side view with visualization of the layered structure.

DESIGN AND SIMULATION

The structure of the vertical 1x4 3D MMI is shown in Fig. 1. The light is guided from the blue single-mode input waveguide on the left side to the MMI section. Single-mode operation at a wavelength of 1550 nm is ensured by choosing a rectangular waveguide with a cross-section of 3.2 µm x 3.2 µm with a refractive index contrast of 0.03 between cladding and core. In the vertical MMI area of the 1x4 3D MMI (Fig. 1 c), a multi-mode field is generated by self-interference of the single-mode input. According to the self-imaging theory [1, 6] and by suitable choice and combination of the parameters MMI length, MMI width and MMI height, four images of the input field distribution with equally distributed intensities and phases are created at the end facet of the MMI, which can be coupled into the four single-mode output waveguides WG1 to WG4. In order to optimize the dimensions of the 1x4 MMI with respect to low losses, low imbalance, and a large offset-tolerance, the layout of the 1x4 3D MMI (Fig. 1) was implemented and simulated in FIMMWAVE. Based on the self-imaging theory [1, 6] all three parameters are correlated with each other and had to be considered simultaneously in the simulation to find the best trade-off. The challenge is to optimally meet the requirements of the 1x4 3D MMI design with respect to these three performance parameters while ensuring a certain tolerance for technological imperfections.

The MMI height is determined by both the height of the waveguide layers and the desired vertical spacing between the waveguide layers of 4.0 µm (Fig. 1). This vertical spacing was chosen to avoid evanescent coupling between the waveguide layers. The MMI has a height of 21.6 µm (center-to-center). In a first variation of the MMI width and length, an optimal point with an imbalance of 0.1 dB and an excess loss of 1.5 dB per optical path plus 6 dB inherent 1x4 MMI loss was determined for a wavelength of 1550 nm. These data were determined for an MMI width of 4.1 µm. To further reduce losses, the simulation was adjusted to add an additional layer below the lowest and above the top waveguide layer (Fig. 1 c). This increase in overall MMI height results in a broadening of the MMI region as a function of MMI length, and for a fixed MMI width, a combination of height and length can be found for which MMI losses are minimal. These additional layers are used for the first time in the PolyBoard 3D PICs.

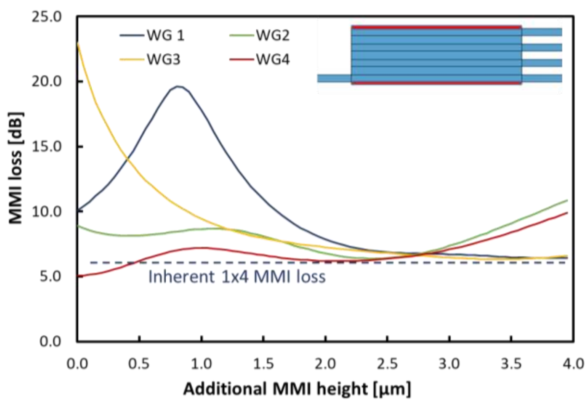

Fig. 2: Simulation of the MMI loss as a function of the additional MMI height at fixed MMI length of 809 µm and MMI width of 4.1 µm per output waveguide at a wavelength of 1550 nm.

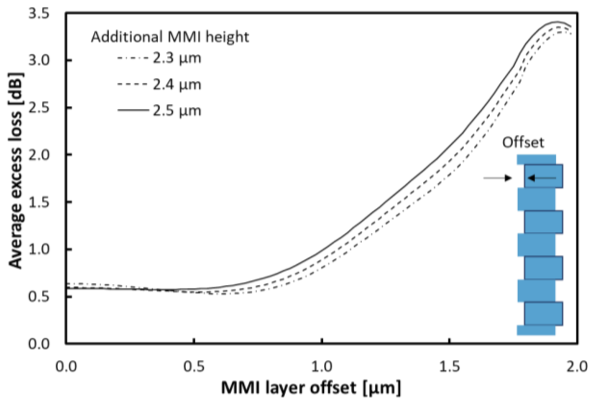

Fig. 3: Simulated average excess loss for all outputs as a function of the variation of the 1x4 3D MMI offset for three different additional MMI heights. To simplify the simulation, the offset was inserted at the four waveguide layers. Here, the offset is the same for all layers and in the same direction.

In the simulation of the additional layers, their influence on the losses and imbalance was considered for different MMI lengths. In Fig. 2, the losses per output waveguide are plotted as a function of the additional height for an MMI length of 809 µm. For an additional MMI height of 2.5 µm, the MMI excess losses are on average 0.6 dB lower (excl. the 6 dB inherent 1x4 MMI losses). In comparison, the imbalance has increased slightly by 0.5 dB.

In the final step, the technology-induced misalignment between the waveguide layers and its effects are investigated to obtain a functional MMI design with large on-wafer yield. The 1x4 3D MMI is fabricated with a total of nine waveguide and intermediate layers (Fig. 1). The offset between these nine layers is created by aligning the mask layers during UV lithography. The 1x4 3D MMI design is expected to have sufficient tolerance to this unavoidable misalignment. To simplify the simulation, it was assumed that the layers have an offset from each other that alternates but always points in the same direction and with the same value to each other. This type of offset represents a worst possible case, since the overlapping contact area of the layers is significantly reduced, drastically affecting the effective width of the MMI. In Fig. 3, the offset was varied for three different additional heights, with the MMI length of 809 µm and the MMI width of 4.1 µm fixed. The figure shows that the additional layers have little effect on the losses due to the offset. However, the design shows sharply increasing losses at an offset > 1 µm. Within the manufacturing accuracy of the layer thicknesses, an additional MMI height of 2.4 µm is targeted.

CHARACTERIZATION

The design from the previous section was fabricated on wafer scale [4]. Fig. 4 shows a top view of a 3D PIC with an initial 1x4 3D MMI (length: 809 µm). The chip was spectrally characterized in a fiber-chip-fiber arrangement. The wavelength dependent losses for all four output waveguides are shown in Fig. 5. The 1x4 3D MMI works in all input-output waveguide combinations. Nevertheless, the significantly increased losses compared to the simulation should be noted. For reference, the losses in the best-case scenario are composed of twice the fiber-chip coupling and propagation losses, which are 1 dB, and the inherent 1x4 MMI losses of 6 dB per path. At a wavelength of 1550 nm, the 1x4 3D MMI coupler has an additional loss of 2.6 dB at best and 6.5 dB at worst case. The MMI losses of about 0.6 dB, which are given by design, are also included here.

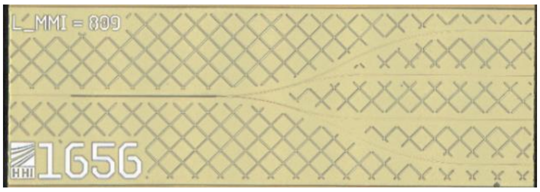

Fig. 4: Microscope image of a fabricated polymer-based 3D PIC with a 1x4 3D MMI (compare Fig. 1b).

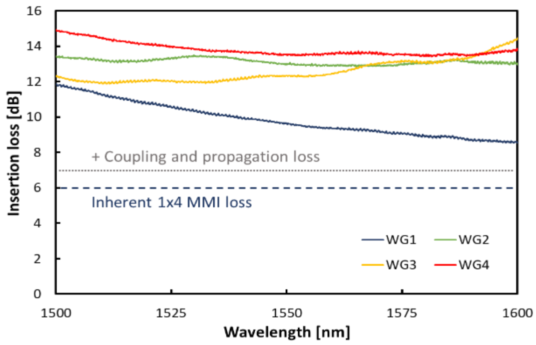

Fig. 5: Measurement results for a 1x4 3D MMI with the parameters: MMI length = 809 µm, MMI width 4.1 µm and additional height 2.4 µm. The insertion loss was measured as a function of wavelength for each output waveguide.

A cross section of the MMI region revealed that the offsets between the layers are much more complex than considered in the simulation, because the waveguides are shifted non-uniformly and in different directions to each other. Table 1 shows the measured offset data, the measured MMI losses at a wavelength of 1550 nm, and the simulation data per waveguide. When the offset was measured, the deviation of the waveguide and intermediate layers from the next deeper layer was determined. To check the influence of the measured offset, the 1x4 3D MMI was fitted with these data. The obtained simulation results are listed in the last column and show that the losses increase significantly for three of the four waveguides due to the offset. Noticeable is the significant deviation from the measured data of waveguide WG3. A possible explanation is a deviation of the actually achieved layer heights from the nominal values. To reduce losses, a reduction of the offset is necessary. This goal can be achieved by introducing a new tool for UV lithography which facilitates the alignment of the layers during the process step and thus increases the accuracy.

Table 1: Comparison of measurement results of the four output waveguides with simulation results

Waveguide No.	**Measurement: Offset [µm]**	**Measurement: Excess loss [dB]**	**Simulation: Excess loss without offset [dB]**	**Simulation: Excess loss with measured offset [dB]**
WG1	0.0 ± 0.3	2.6	1.1	2.7
WG2	0.0 ± 0.3	6.0	0.4	4.1
WG3	- 1.9 ± 0.3	5.3	1.0	0
WG4	0.3 ± 0.3	6.5	0.2	3.0

CONCLUSION

The designed, fabricated and characterized 1x4 vertical MMI connecting four vertically stacked waveguide layers is the first device of its kind. To implement the 1x4 3D MMI, a design was created using a parameter set for height, length and width with low excess losses of 0.7 dB and an imbalance of 0.9 dB. Principle functionality was demonstrated despite higher losses. Reducing the offset between the waveguide layers has a major impact on reducing excess losses from average of 5.1 dB to 0.7 dB and the imbalance by 3.5 dB. Especially in the lithography process, there are further possibilities, such as picture grabbing, to reduce this offset. In addition, the device presented here opens up new possibilities for implementing crossing-free optical switching matrices, small-footprint 3D optical phased arrays, and beam forming networks in 3D photonic integrated circuits.

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