Integrated Programmable Mode Generator and Multiplexer on a Silicon Chip

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Abstract We design and demonstrate a programmable mode generator based on an integrated orbital angular modes multiplexer. We generate eight linear polarized (LP) modes with the proof-of-concept device.

Introduction

With the everlasting pursuit of faster data transmission and higher spectral efficiency, researchers worldwide have been actively exploring different technologies to increase the transmission capacity of optical communication systems. Various sophisticated optical modulation formats as well as advanced multiplexing techniques have been studied and developed[1], [2]. Spatial division multiplexing (SDM) provides an additional degree of freedom in addition to the conventionally exploited dimensions of light such as amplitude, phase, and wavelength[2]. In particular, mode-division multiplexing (MDM) allows simultaneous transmission of multiple modes within a fiber for substantially increased spacial density. MDM can be implemented using different mode sets such as orbital angular momentum (OAM)[3], linearly polarized (LP) modes[5], and vector modes[2]. They have distinct advantages and the optimal choice may vary across application scenarios. A hybrid optical network consisting of different types of SDM fiber links is thus foreseen. An ideal mode multiplexer should be reconfigurable to support arbitrary mode sets.

SDM devices in photonic integrated circuits (PICs) have attracted significant interest thanks to their compact footprints and potential for large-scale integration[3, 5]. In our previous work, we demonstrated an OAM multiplexer on silicon on insulator (SOI) chip, that supported generation of OAM modes having orders as high as 11 in circular polarization with different input signals[5, 17]. Generally, photonic circuits are designed with a fixed functionality. The needs for accelerated development of flexible and advanced optical functions spurred the recent research on programmable photonic integrated circuits[9, 10]. With this new programmable PIC technology in the horizon, MDM multiplexers can also be designed to be reconfigurable such that different optical modes can be generated and multiplexed for different SMD fibers without altering the input signal.

In this work, we demonstrate a first of its kind, a programmable MUX on a silicon photonic chip that can generate an arbitrary mode. It consists of a reconfigurable mesh that enables arbitrary combinations of a number of OAM modes consecutively. For a proof of concept, we use this programmable chip to generate both OAM and LP modes.

Design and fabrication

The schematic of our proposed device is shown in Fig. 1. It consists of two functional blocks. The first one is an OAM generator circuit (OAM-GC) that accepts a number of single-mode waveguide inputs and coverts each of them to a specific OAM mode from the same output aperture. The second functional block is a linear operation circuit (LOC) that realizes an arbitrary combination of its input channels. The outputs of the LOC are connected to the inputs of the OAM-GC.

According to[10], the relationship between LP modes and OAM modes in a few-mode fiber (FMF) is expressed in Equation 1. The generation of a LP mode requires four circularly polarized OAM modes of the same order to be combined with specific phase.

\[
LP_{even}^{l_x} = OAM_{l}^+ + OAM_{l}^- + OAM_{l+}^- + OAM_{l-}^-
\]

\[
LP_{odd}^{l_y} = OAM_{l}^+ - OAM_{l}^- - OAM_{l+}^+ + OAM_{l-}^-
\]

\[
LP_{even}^{l_y} = OAM_{l}^+ + OAM_{l}^- - OAM_{l+}^- - OAM_{l-}^-
\]

\[
LP_{odd}^{l_y} = OAM_{l}^+ + OAM_{l}^- - OAM_{l+}^- + OAM_{l-}^-
\]

(1)

The LOC (light yellow background) contains a dual-stage MZI matrix with 14 input channels. The first stage of the MZI matrix includes 7 MZIs which have identical design parameters: they
all have balanced arms and thermo-optic phase shifters to impact the light splitting. As forming a LP mode requires four OAM modes, another six MZIs are placed as the second stage. The 0th order OAMs are not involved in forming LP modes thus are not routed to any MZI in the second stage. The dual-stage MZI matrix can simultaneously excite four OAM modes with equal intensity when the MZI matrix is correctly biased.

The OAM generator circuit is designed following the methodology in ref.5. In this device, OAM multiplexer has a 9-antenna-ring as emitter and supports OAM 14 modes up to the third order. The antenna has 2-dimensional gratings and can emit light vertically with 4dB loss. More importantly, when the antenna combines light from the 2 × 2 MMI with 90 degree relative phase, we can directly generate circularly polarized beam, satisfying one important requirements in Equation 1.

Our chip was fabricated using a standard 220-nm silicon photonics process. The photograph of the fabricated chip is shown in Fig. 2. As indicated by the light yellow background, the linear operation circuit is in the middle right of the chip. The input fiber array are optically packaged with the edge couplers. The OAM generator circuit on the top and the bottom sides contribute to the generation of OAM modes of left circular and right circular polarizations, respectively. The emitter of the device is situated at the middle left of the chip.

**Chip calibration**

The LOC and the OAM-GC are calibrated separately. The two-stage MZI matrix in the linear-operation circuit determines the number of OAM modes that are simultaneously excited and their relative intensity and phase. We include 10% taps at the end of both stages of the MZI matrix to correctly bias the MZIs to perform the ideal combination. The calibrated MZI matrix has two configurations: to generate LP modes, input light experiences two times of 50:50 splitting and excites four OAM modes; to generate OAM modes, MZIs are biased at through or bar state and the input light only generates one OAM mode. The relative phase between the OAM modes is controlled by the phase shifters before the star couplers.

The OAM multiplexer requires calibration in amplitude uniformity and phase error in both left and right circular polarization. A 4-f system is used to observe the near field of the generated field and to apply attenuation through on-chip optical attenuators, increasing the uniformity among antennas and improving the quality of the generated beams. After that, we inject 2nd order OAM generated with a vortex plate to calibrate the phase errors (using the chip as a demultiplexer). A perfectly calibrated phase suppresses 13 unwanted modes and maximizes the power in the intended mode. We achieved -14dB worst-case crosstalk in the calibration of the left circular and -8dB for the right circular, which can be further improved by optimizing the calibration algorithm.5.

The side view of our experimental setup is presented in Fig. 3. The optically and electrically packaged chip is placed on a five axis stage with heat sink underneath. The generated beam propagates vertically into the free-space assem-


Fig. 4: (a)∼(d) Intensity non-uniformity calibration and phase error of the OAM generation circuit. (e)∼(h) Far field intensity profile of the generated LP modes

Results

We show the calibration result of our OAM generator circuit in Fig. 4. We calibrate OAM modes with left circular polarization (LCP) and right circular polarization (RCP) individually. We plot the crosstalk distribution before calibration in Fig. 4a. The crosstalk is measured by shining the OAM mode generated through vortex plate onto the emitter and measure the power at all outputs. The power in the unwanted outputs create crosstalk. The crosstalk of output $i$ is defined as $XT_i = P_i/ P_{target}(i \in (1, 14), i \neq target)$. The worst-case crosstalk before tuning is 4.4dB for LCP and -1.5dB for RCP. As we apply tuning to improve intensity non-uniformity and correct phase errors, we measured a much better average crosstalk for both polarizations (Fig. 4b), and we believe that the crosstalk for RCP can be further reduced given more optimization time. By comparing the intensity distributions in Fig. 4c and Fig. 4d, we can intuitively identify a more uniformed intensity distribution from the near-field pattern in both polarizations.

Once we calibrate our OAM generator, we bias our linear operation circuit at LP mode configuration and tune the relative phase between the excited OAM modes. We target at all the degenerates of $LP_{11}$ and $LP_{21}$ modes. Notice that the phase tuning for LP modes of the same order is done only once, for example, we optimize the phase to generate $LP_{11}^{even}$, the same tuning set also works for the generation of other degenerates.

We capture the far-field intensity distribution under LP configuration, $LP_{11}$ in the first row and $LP_{21}$ in the second row Fig. 4e∼h. The number of lobes and their orientations fit with our expectation. The recorded image is a little bit tilted due to our camera position. The intensity of the lobes however varies, especially in $LP_{11}^{odd}$ and $LP_{21}^{odd}$. We believe the relative higher crosstalk with RCP is responsible. The relative phase between the OAM modes can also be optimized further. In the future, we will improve the optimization routine based on quantitative analysis of the mode quality.

Conclusion

In conclusion, we have demonstrated a programmable silicon photonic chip that can in principle generate an arbitrary mode through the combination of OAM modes. For proof of concept, we showed both OAM and LP modes from the same device. Our device may provide a critical function for future reconfigurable SDM fiber-optic systems and can also be used for mode generation in free space optical communications systems.

Acknowledgements

We thank Nathalie Bacon and CMC Microsystems for their technical support.

References


