Flexible on-chip mode-division switching with a new mode converter design

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There have been some significant advances in optical-fiber multimode communications. And important effort in on-chip communication has also been recently reported for realizing mode-division multiplexing (MDM). Because of the difficulty in lack of mode converter which can freely perform mode converting function among different waveguide modes, flexible on-chip mode-division switching communication has been rarely reported. Here we show the first demonstration of mode converter which can convert an arbitrary waveguide mode into any other modes with the help of phase tuning. With that mode converter, two flexible on-chip mode-division switching architectures are proposed. That architecture is compatible with wavelength-division multiplexing (WDM) and can enable further scaling of the on-chip communication bandwidth. Our demonstration suggests great potential of mode-divisional switching in the vision of fully flexible, dense, on-chip optical networks.

The data switching is an important function for flexible and advanced optical networks and considerable research has been given to wavelength division multiplexed optical-fiber systems. In these systems, data exchange, which is also known as wavelength exchange or interchange in the wavelength domain, is an important technique which can efficiently make use of network resources and improve network performance. The switchable and flexible function is also significant for advanced and reconfigurable photonic-integrated optical network because of data routing between the processor and memory systems on a chip multiprocessor. However, because of the expensive cost and complicated process requirement, it is hard to realize the multiple laser sources with different wavelengths for on-chip optical interconnection applications. Space-division multiplexing (SDM), which only employs a single wavelength carrier, provides a new dimension to meet the growing demand on transmission capacity of our communication systems, by utilizing the spatial modes to carry multiple optical signals simultaneously. Significant effort in optical-fiber multimode communications has been put in recent years into realizing mode-division multiplexing. Numerous advances on multimode communication in fibers have so far been reported, such as space-division multiplexing in multi-core fibers\textsuperscript{1,5} and mode-division multiplexing in few-mode fibers\textsuperscript{6-14}. Fiber communications are also trying to combine multimode operation with other multiplexing technologies, such as WDM\textsuperscript{15}, to further scale the communication bandwidth transmitted per fiber. For the demand of on-chip and off-chip high-bandwidth-density interconnects, photonic-integrated mode division multiplexing attracts more and more attentions by taking advantages of increasing the
transmission capacity efficiently. Several designs for on-chip mode multiplexers have been proposed previously, including designs based on Mach-Zehnder interferometers\textsuperscript{16,17}, multimode interference couplers\textsuperscript{18-20}, asymmetric directional couplers\textsuperscript{21-23} and y-junctions\textsuperscript{24-26}. Previous implementations of mode-division multiplexing switch\textsuperscript{27} and mode exchange using tapered directional coupler\textsuperscript{28} have also been demonstrated. However, those proposed devices, no matter mode multiplexers, multimode switches or mode exchange schemes, suffer from several drawbacks, including a limited number of optical modes or a lack of selectivity among user’s wanted modes, which are not suited to fully flexible, dense, on-chip optical networks. Some of the key challenges of realizing on-chip MDM-enable flexible interconnects lie in creating the mode converter and (de)multiplexer which can selectively deal with arbitrary mode. But it is really hard to finish those designs, because the mode confinements in a multimode waveguide vary significantly between the different modes. That is why on-chip data switching based on MDM is rarely considered, while it is highly desirable to increase robustness and throughput of the chip-level network utilizing mode multiplexing.

Mode converter

Here, we present a new mode converter design, as shown in Figure 1a, which accomplishes the mode conversion function from fundamental mode to any other optical modes and provides wide bandwidth operation. It comprises a middle multimode transport waveguide consisting of several sections with tapering widths from a single mode waveguide to different multimode waveguides, and two single mode waveguides extending along both sides of the middle multimode waveguide. To show a mode conversion function from TE0 to TE1 and TE0 to TE2, that middle multimode waveguide tapers widths ranging from 0.45 um to 1.41 um. When the multimode waveguide width corresponds to 450 nm, 930nm or 1.41 um, the effective indices of TE0, TE1 or TE2 modes, respectively, match the effective index of the TE0 mode of the 0.45 um waveguide\textsuperscript{29}. The separation gaps between the upper lower single mode waveguide and multimode waveguide at TE0, TE1 and TE2 coupling regions are 250 nm, 200 nm and 200 nm, respectively. In that middle multi-mode waveguide, there is a fixed phase difference between the odd modes which are respectively excited by the upper and lower single mode waveguide with their fundamental mode inputting, and so does the even modes. Several phase-shifting elements are added to the upper single mode waveguide section to accomplish each mode conversion function. When single mode light is input into left side of the middle waveguide, it will be first split into two beams propagating in the upper and lower waveguides. And by tuning their phase difference, destructive interference or constructive interference can be controlled to perform the mode conversion function. Once mode conversion is accomplished, the converted mode will propagate steadily in the middle multimode waveguide.
A further improved design is shown in Figure 1b. That structure accomplishes the mode conversion function from an arbitrary optical mode to the other mode, by converting the arbitrary mode first into TE0 mode which is then be converted to any other wanted mode. That mode conversion function, like the wavelength conversion function to WDM, is the key technology to mode-division multiplexing.

For the convenience of simulation, here the width of the upper single mode waveguide was changed to realize the phase tuning. And the mode conversion from TE0 mode to the TE0, TE1, or TE2 modes and the conversion from TE2 mode to TE1 mode are taken as the examples. Based on 3D FDTD method, the simulated electric field distribution of mode conversion function among those different modes with our mode converter is shown in Figure 2.
The power of converted mode from different modes can be computed with 3D FDTD and depicted in Fig. 3. It shows the transmission spectrum of mode conversion among different modes. The simulated insertion loss of the conversion from TE0 to TE0 at $\lambda=1.550\text{nm}$ is about 0.2 dB. The insertion loss of mode conversion from TE0 to TE1 at $\lambda=1.550\text{nm}$ is about 0.2 dB. And the insertion loss from TE0 to TE2 at $\lambda=1.550\text{nm}$ is 0.5 dB. The insertion loss from TE2 to TE1 at $\lambda=1.550\text{nm}$ is about 0.6 dB. All of those mentioned mode conversion function performs a broadband performance in C-band. There are two main things contributed to the insertion loss. One is the growing amount of bends, tapers and the coupling times, and another is the imprecise phase tuning. That insertion loss can be reduced by increasing the radius of bend, extending the length of taper and further optimizing on the waveguide coupling region. To realize a precise phase tuning, electro-optic effect or thermo-optic effect can selected for users in actual silicon chip fabrication.
Figure 3 | Insertion loss of mode conversion among different modes.

Because of the strong refractive index tuning capacity of thermo-optic effect\textsuperscript{30}, it can be used to control the phase difference between those two single mode arms. To avoid absorption, the optical mode should be well separated from the heater, and should also be close enough to couple heat into the waveguide. Some configuration parameters of the waveguide and heaters can refer to the published paper\textsuperscript{31}. The single mode waveguide in this paper is 450 nm wide by 250 nm thick.

Mode-division switching architecture

Based on the mode converter shown in this paper, here we present two new communication architecture designs which can accomplish the flexible mode-division switching function. The first design, shown in Figure 4a, comprises the mode converter with mode (de)multiplexers\textsuperscript{23} connected at its input and output port. With the help of mode converting function from that converter, each inputting light from the left side can be switched to any of the outputting port on the right. That is a simple design based on the mode converter presented in this paper, but its disadvantage is that light at the left side cannot be injected at the same time. Because the mode converter can only perform the mode converting function on one waveguide mode at one time, it cannot work on different modes simultaneously.

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Figure 4 | The schematics of the proposed mode-division switching architectures. a, The schematic diagram of the simple architecture design used for mode-division switching. b, The schematic diagram of the improved architecture design used for mode-division switching.
The improved design is shown in Figure 4b. There is a mode converter connected at each input port in this design. And a mode de-multiplexer is connected with that each mode converter. Light from that de-multiplexer can be coupled into the output port on the right with the help of another multiplexer. Because of the mode converting function of the mode converter, each inputting light from the left side can be switched into any of the outputting port on the right. The problem that light at the left side cannot be injected at the same time in the first design is solved in this improved design. And the most important is that the simultaneously different inputting light from the left side can be switched to output from the same port or each to different output ports on the right. So that is a non-blocking and flexible switching architecture and there is obviously improvement on its communication capacity compared to the common reported silicon switch matrix with the same scale.

Here we extract the S parameters which are from the 3D FDTD simulation results of those basic elements included in the above mentioned architecture to show the propagating performance of the second design in Figure 4b. The propagation that TE0 mode input into the first port on the left side and then TE0 output from the second port on the right is taken as the example. In that propagation, it is necessary to convert the input TE0 mode first into TE1 mode, and then it can be coupled into the second port on the right. The transmission spectrum is shown in Figure 5.

In summary, a novel mode converter design which can convert an arbitrary waveguide mode into any other mode with the help of phase tuning have been first demonstrated in this paper. That free mode conversion function is the key technology for mode-division multiplexing. In particular, we present two new communication architecture designs which can accomplish the flexible mode-division switching function. Our work represents an important step towards the realization of a practical on-chip mode-division multiplexing application. For its compatibility with WDM, it can be combined with wavelength-divisional photonic switching to further improve the performance of integrated optical networks.
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