Error-Tolerant Integrated Optical Unitary Processor based on Multi-Plane Light Conversion

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Abstract: We experimentally demonstrate error-tolerant optical unitary processors with multiport directional couplers. Thanks to the inherent redundancy of the multi-plane light conversion scheme, equivalent performance is obtained in the presence of large fabrication errors. © 2022 The Author(s)

1. Introduction

An integrated optical unitary processor (OUP) can convert N mutually orthogonal modes into arbitrary N output modes in a reconfigurable manner. The OUP can be employed in various applications, including all-optical multi-input-multi-output (MIMO) processors in space-division-multiplexed (SDM) transmission systems, linear matrix processors for optical neural network hardware, and quantum photonic processors for task-specific computations [1,2]. While OUPs have conventionally been implemented by cascading 2×2 Mach-Zehnder interferometers (MZIs) in a mesh architecture [3,4], they are generally sensitive to a small fabrication error due to the strict requirement to achieve 50:50 beam splitters at each MZI [5]. In addition, the number of MZIs scales quadratically with the matrix size N, so that this requirement becomes more and more severe as N increases [6]. To compensate for the realistic errors, several schemes of using redundant MZIs [7,8], global optimization [5], and local error correction [9] have been proposed. These approaches, however, require additional components and become increasingly more difficult to implement as N increases. Therefore, an inherently error-tolerant and scalable OUP is desirable.

As an alternative approach to realize OUP, the multi-plane light conversion (MPLC) scheme has been proposed and demonstrated [10-15]. Unlike the MZI-based OUP (MZI-OUP), the MPLC-based OUP (MPLC-OUP) does not require a specific transformation at each node. As a result, it has been numerically demonstrated that the overall performance is insensitive to the exact device geometries [6,16]. However, experimental demonstration to confirm this error tolerance of MPLC-OUP has not been reported to our knowledge.

In this paper, we experimentally investigate the error tolerance of the MPLC-OUPs with multiport directional couplers (DCs) and demonstrate its robustness against various deviations in the waveguide geometries. By comparing several silicon photonic 4×4 OUPs with different parameters, we show that similar performance is obtained even when the gap G and length L of the multiport DCs deviate by 25 nm and 5 μm, respectively.

2. Integrated MPLC-based OUP

The silicon photonic 4×4 OUP device fabricated in this work is shown schematically in Fig. 1. It consists of four stages of 4-port DCs and thermo-optic (TO) phase shifter arrays. The 4×4 transfer matrix $\mathbf{T}$ describing the transformation of complex amplitudes from the four input ports to the four output ports is expressed as

$$\mathbf{T} = \mathbf{\Phi}_4 \cdot \mathbf{M} \cdot \mathbf{\Phi}_3 \cdots \mathbf{M} \cdot \mathbf{\Phi}_0 , \tag{1}$$

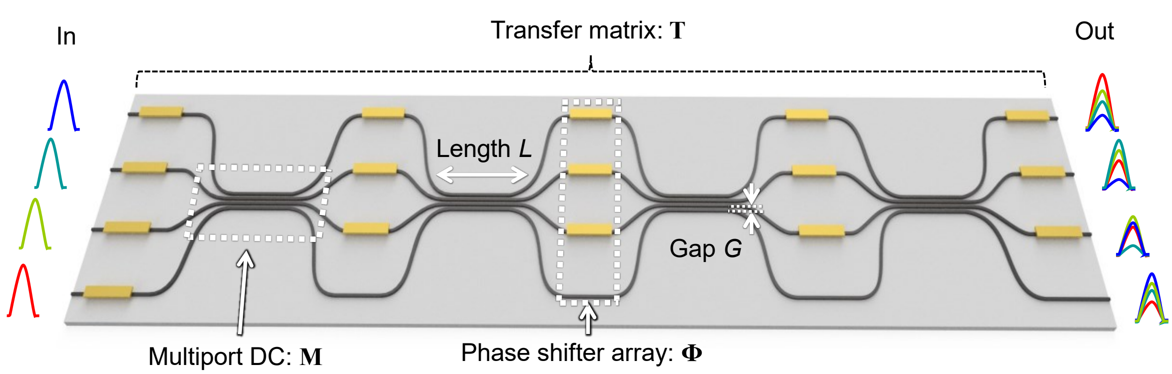

Fig. 1. Schematic of 4×4 OUP using four stages of 4-port DCs.

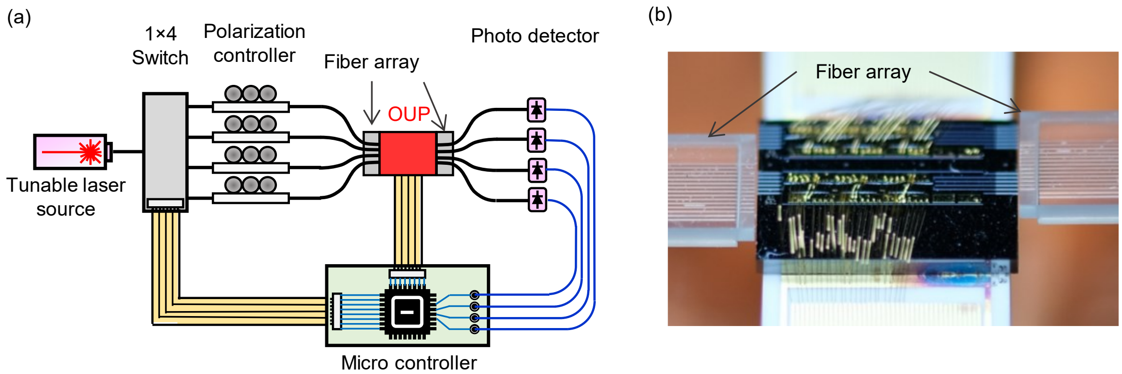

Fig. 2. (a) Experimental setup. Polarization states of all inputs are adjusted to TE. The microcontroller controls the MEMS switch and collects the signals from PDs to optimize the phase shifters according to the simulated annealing algorithm. (b) Photograph of the mounted OUP.

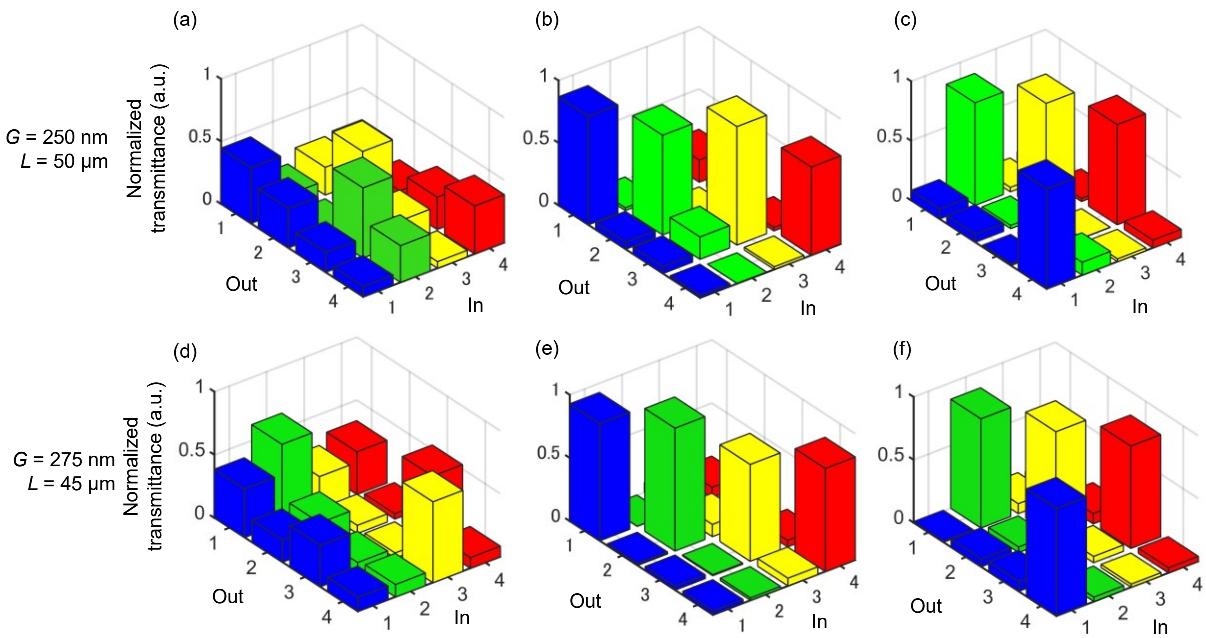

Fig. 3. Measured optical transmittance of the OUPs using multiport DCs with (G, L) = (250 nm, 50 μm) (a- c) and (275 nm, 45 μm) (d-f). (a) and (d) show the passive transmittance without driving phase shifters. (b),(c),(e) and (f) show the cases after optimizing the phase shifters to obtain [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1] (b, e) and [0 0 0 1; 1 0 0 0; 0 1 0 0; 0 0 1 0] (c, f), respectively.

where $\mathbf{M}$ is a fixed 4×4 unitary transfer matrix describing the mode mixing in each 4-port DC, $\mathbf{\Phi}_i$ $(i = 0, 1, \dots 4)$ is a diagonal matrix representing the phase shift applied at the i-th phase shifter stage. Similar to the MPLC device realized using free-space optics [17], the integrated MPLC-OUP can implement arbitrary unitary transformations by adjusting the phase shifters properly [11].

It is important to note that the unitary matrix $\mathbf{M}$, responsible for mixing complex amplitudes, does not have to be in a specific matrix form. Instead, it is only requested to provide substantial coupling between adjacent waveguides, so that the multiport DCs can be designed with great flexibility. Therefore, even if the waveguide geometries of each multiport DC deviate from the initial design, the overall performance of the OUP is insensitive [6,16].

3. Experimental setup and results

To demonstrate the robustness of the OUP with multiport DCs, we experimentally compare the performance of silicon photonic 4×4 OUPs, having different values of gap G and length L (see Fig. 1 for definition) in their 4-port DCs. In addition to the previously demonstrated OUP with (G, L) = (275 nm, 50 μm) [12], we tested two types of OUPs with (G, L) = (250 nm, 50 μm) and (275 nm, 45 μm). All OUPs were fabricated on a silicon-on-insulator (SOI) chip with a 220-nm-thick silicon layer and 3-μm-thick buried oxide (BOX) layer. The circuit was composed of five stages of

Table 1. Measured performance of 4×4 OUPs with 4-port DCs

Parameters of multiport DC (G [nm], L [μm])	Performance of OUP Crosstalk (dB)	MSE (dB)
(275, 50) [12]	-12.1	-23.4
(250, 50)	-11.5	-21.6
(275, 45)	-12.2	-24.5

4×4 multiport DCs. Similar to Ref. [11,12], the first stage of DC was used as a mode mixer, and four stages of phase shifters were tuned to implement the desired matrix.

Figures 2(a) and (b) show the experimental setup and the photograph of the mounted chip, respectively. A microcontroller was employed to sequentially select one of the four input ports by controlling a 1×4 optical micro-electro mechanical systems (MEMS) switch and collect the signals from four photodetectors (PDs) to measure transmittance to all output ports. After testing all input ports, the objective function f was calculated, from which the next phase shifter conditions were decided. Each of these iterations took around 5.6 ms, which was limited by the switching time of the MEMS switch, while the entire optimization converged typically after around 120 seconds (~12,600 iterations). After convergence, all phase shifters were set to the optimized condition.

Figure 3 shows the normalized total transmitted power measured at each output port before and after optimizing phase shifters for two types of OUPs: (G, L) = (250 nm, 50 μm) and (275 nm, 45 μm). Before optimizing phase shifters, severe crosstalk is observed at output ports due to the coupling inside the mode mixer [see Fig. 3(a) and (d)]. In contrast, Figs. 3(b) and (e) show the results under optimized phase shifter conditions to implement the unit matrix: [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1]. In addition, Figs. 3(c) and (f) show the cases for a different target matrix: [0 0 0 1; 1 0 0 0; 0 1 0 0; 0 0 1 0]. From these results, we can confirm the reconfigurable operations in both OUPs. The average crosstalk and mean-square error (MSE) after optimization in each case are summarized in Table 1. We also list the case of (G, W) = (275 nm, 50 μm) from the previous work [12]. In all cases, the MPLC-based OUPs show comparable performance, implying that the MPLC-OUP with multiport DCs has excellent robustness against fabrication errors. Since the fabrication errors can be regarded as deviations of the transfer matrix in each mode mixer, similar robustness is expected against other types of perturbations such as wavelength shift, temperature change and so on.

4. Conclusion

We have experimentally demonstrated the robustness of integrated OUP based on the MPLC concept. By measuring several silicon photonic 4×4 OUPs with different design parameters, we show that similar performance is obtained even when the gap and the length of the multiport DCs change significantly. These results strongly support the inherent robustness of MPLC-OUPs, which should be advantageous in realizing large-scale OUPs for diverse applications.

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Reference

[1] W. Bogaerts, et al., "Programmable photonic circuits," Nature **586**, 207-216 (2020).
[2] G. Wetzstein, et al., "Inference in artificial intelligence with deep optics", Nature **588**, 39-47 (2020).
[3] M. Reck, et al., "Experimental realization of any discrete unitary operator," Phys. Rev. Lett. **73**, 58 (1994).
[4] W. R. Clements, et al., "Optimal design for universal multiport interferometers," Optica **3**, 1460 (2016).
[5] S. Pai, et al., "Matrix optimization on universal unitary photonic devices," Phys. Rev. Appl. **11**, 064044 (2019).
[6] R. Tanomura, et al., "Scalable and robust photonic integrated unitary converter based on multiplane light conversion," Phys. Rev. Appl. **17**, 024071 (2022).
[7] D. A. B. Miller, "Perfect optics with imperfect components," Optica **2**, 747-750 (2015).
[8] R. Hamerly, et al., "Design of asymptotically perfect linear feedforward photonic circuits," in Optical Fiber Conf. (OFC), W2A.5 (2022).
[9] S. Bandyopadhyay, et al., "Hardware error correction for programmable photonics," Optica **8**, 1247-1255 (2021).
[10] J. F. Morizur, et al., "Programmable unitary spatial mode manipulation," J. Opt. Soc. Am. A. **27**, 2524-2531 (2010).
[11] R. Tang, et al., "Reconfigurable all-optical on-chip MIMO three-mode demultiplexing based on multi-plane light conversion," Opt. Lett. **43**, 1796-1801 (2018).
[12] R. Tanomura, et al., "Robust integrated optical unitary converter using multiport directional couplers," J. Lightwave. Technol. **38**, 60-66 (2020).
[13] R. Tang, et al., "Ten-port unitary optical processor on a silicon phonic chip," ACS Photonics **8**, 2074-2080 (2021).
[14] R. Tanomura et al., "Monolithic InP optical unitary converter based on multi-plane light conversion," Opt. Express **28**, 25392-25399 (2020).
[15] R. Tanomura et al., "Integrated InP optical unitary converter with compact half-integer multimode interferometers," Opt. Express **29**, 43414-43420 (2021).
[16] R. Tanomura, et al., "Entropy of mode mixers for optical unitary converter based on multi-plane light conversion," in Conference on lasers and electro-optics Pacific Rim (CLEO-PR), CWP13A-02 (2022).
[17] N. K. Fontaine et al., "Laguerre-gaussian mode sorter," Nat. Commun. **10**, 1865 (2019).