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Optical Unitary Conversion of Multi-Wavelength Dual-Polarization Channels using Integrated Multi-Plane Light Converter

Ryota Tanomura [1], Takuo Tanemura [1], and Yoshiaki Nakano [1]

[1] the University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
Phone: +81-3-6891-9306 E-mail: ryota_tanomura@hotaka.t.u-tokyo.ac.jp

Abstract

Integrated optical unitary converter (OUC) is receiving a great interest for optical communication, quantum computing, and deep learning applications. Previously demonstrated OUCs assume a fixed wavelength and a polarization state at the input. In this paper, we demonstrate that the multi-plane light conversion (MPLC)-based OUC with multiport directional couplers (DCs) can provide arbitrary and independent unitary conversions to dual-polarization multiple-wavelength channels at the same time. This is due to the inherent flexibility of the MPLC concept as well as strong polarization/wavelength dependence of a silicon-photonic multiport DC.

1. Introduction

An optical unitary converter (OUC) can convert mutually orthogonal spatial modes into arbitrary spatial modes. It is widely researched for optical communication, deep learning, task-specific quantum computing, and so on [1]. While OUCs can be implemented by cascading Mach-Zehnder interferometers (MZIs) [1,2], such architecture requires accurate 50:50 beam splitters in each MZI [3,4]. As a result, the directional couplers (DCs) or multimode interference (MMI) couplers, which are commonly used as the beam splitters, need to be designed precisely for the specific polarization and wavelength of interest. Thus, the MZI-based OUC cannot be directly extended to wavelength- and polarization-division-multiplexed signals.

In this paper, we demonstrate that an OUC using multiport DCs can realize independent unitary conversion for multiple wavelength and polarization channels simultaneously. This OUC is based on the multi-plane light conversion (MPLC) [4-6] principle, which does not require a specific transformation, unlike the MZI-based OUC. The MPLC-based OUC consists of cascaded stages of dense unitary mixing layers and arrayed phase shifter layers. A multiport DC, which is used as the mixing layer, exhibits different unitary transformations depending on the wavelength and polarization state. Therefore, with a sufficient number of stages, the MPLC-based OUC using multiport DC can realize independent and arbitrary spatial unitary conversions of multiple wavelength and polarization channels.

2. Schematic of proposed device

Figure 1 shows of the schematic the proposed architecture.

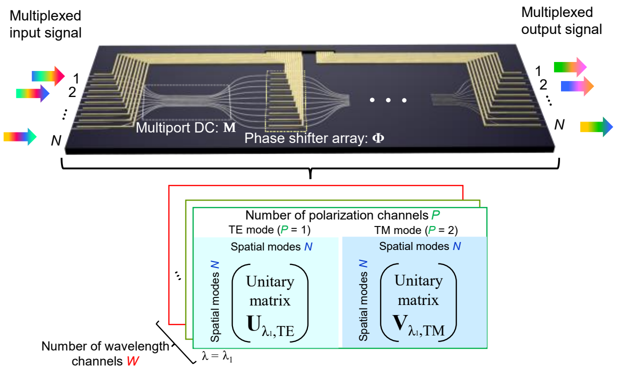

Fig. 1. Schematic of the OUC using multiport directional couplers. When the wavelength- and polarization-multiplexed N-dimensional complex vector are input, the OUC can apply independent and arbitrary unitary transformations to all wavelength and polarization channels.

The MPLC-based OUC consists of cascaded L multiport DCs and L+1 phase shifter arrays, where L is a number of stages. We assume wavelength- and polarization-division multiplexed signals are input to all N ports. For the MPLC scheme to operate properly, each N-port DC needs to provide dense $N \times N$ unitary mixing [4]. An N-port DC assures unitary mixing among all N ports without inherent optical loss, regardless of the operating wavelength and polarization. At the same time, it generally has strong wavelength and polarization dependency, so that different unitary transformations can be applied to different polarization/wavelength channels. With sufficiently large L, therefore, we can expect that arbitrary unitary conversion may be achieved for each polarization/wavelength channel using a single device.

Considering the freedom of the unitary matrix, the number of stage L should satisfy

$$L \geq NPW, \qquad (1)$$

where P and W are the numbers of polarization and wavelength channels, respectively. The total number of phase shifters is $N \times L$. Similar to the previous works [4,6], we adjust the phase shifters to examine whether it is possible to simultaneously achieve desired unitary transformations for all PW independent channels.

3. Results

Numerical simulation is carried out to investigate the feasi-

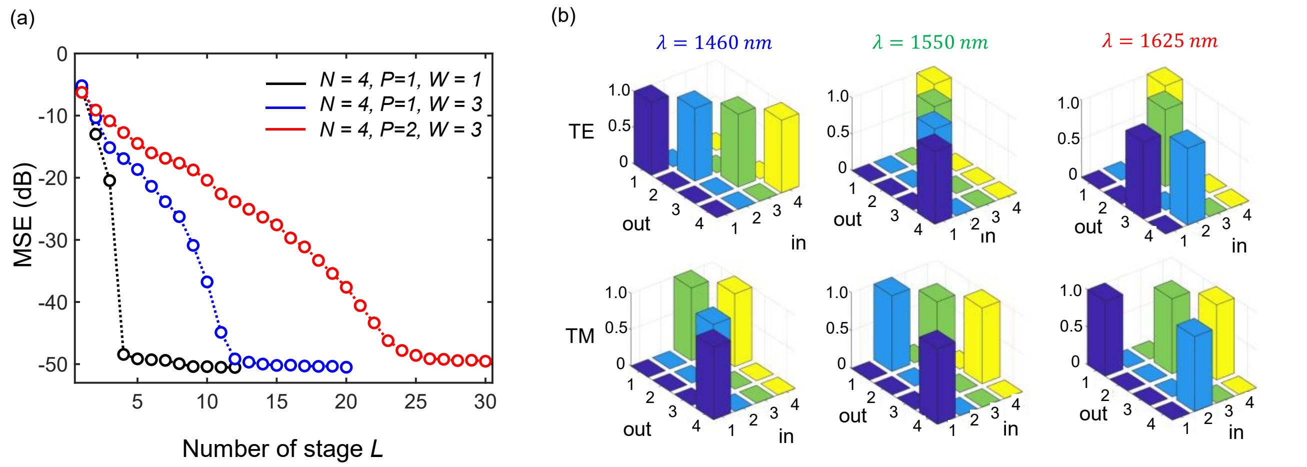

Fig. 2. (a) Calculated MSE after optimizing the phase shifters as a function of L with $(N, P, W) = (4, 1, 1)$, $(4, 1, 3)$, and $(4, 2, 3)$. (b) Obtained $\{\mathbf{U}'\}$ in an example case of realizing different permutation matrices $\{\mathbf{U}\}$ for six wavelength/polarization channels.

bility of simultaneous unitary conversions for multiple wavelength and polarization channels. We compare three cases with $(N, P, W) = (4, 1, 1)$, $(4, 1, 3)$, and $(4, 2, 3)$, where we set the wavelengths at 1460 nm, 1550 nm, and 1625 nm. Standard silicon photonic circuit with 440-nm waveguide width and 220-nm-thick silicon-on-insulator (SOI) device layer is assumed. The multiport DC is designed to have the gap and the coupler length of 250 nm and 40 µm, respectively. The transfer matrix of multiport DC is calculated by the eigenmode expansion method (EME) at each wavelength/polarization channel. We assume ideal lossless phase shifters, each driven independently by an 8-bit digital-to-analog converter (DAC).

In each case, we generate 24 sets of Haar random $N\times N$ unitary matrices $\{\mathbf{U}\}$ as the target transformations for all WP wavelength/polarization channels. Also, let $\{\mathbf{U}'\}$ be the actual transfer matrices realized by the OUC. Then, the deviation between $\mathbf{U}'$ and $\mathbf{U}$ is evaluated by the mean-square-error (MSE), which is defined as

$$\mathrm{MSE} = \frac{1}{W\times P}\sum_{w,p} \frac{1}{N^2}\sum_{j=1}^{N}\sum_{i=1}^{N}\left|(\mathbf{I}_{w,p})_{ij} - (\mathbf{U}'_{w,p}\mathbf{U}^{-1}_{w,p})\right|^2 , \quad (2)$$

where $\mathbf{I}$ is an $N\times N$ identity matrix. We employ the simulated annealing algorithm in tuning all phase shifters to minimize the MSE.

Figure 2(a) shows the MSE as a function of the numbers of stages L after training all phase shifters. In all cases, the MSE is suppressed below -40 dB when $L \geq NPW$. Owing to the strong wavelength/polarization sensitivity of the N-port DCs assumed in this work, similar OUC performance is obtained for all wavelength/polarization channels compared with the single wavelength and polarization case. Figure 2(b) shows the obtained $\{\mathbf{U}'\}$ in an example case, where $\{\mathbf{U}\}$ is set to be different permutation matrices for respective wavelength/polarization channels.

4. Conclusions

We have demonstrated that an MPLC-based OUC with multiport DCs can be designed to realize independent unitary transformations for polarization- and wavelength-multiplexed input signals. Due to the inherent flexibility of the MPLC scheme and the strong wavelength/polarization dependence of an silicon-photonic multiport DC, the proposed OUCs can be configured to perform independent unitary conversions for dual-polarization channels at 1460, 1550, and 1625-nm wavelengths. These results show that the MPLC-based OUC can be extended to multiple wavelength and polarization channels by simply adding extra number of stages without the need for wavelength/polarization demultiplexers. This should be useful particularly for optical communication applications, where all-optical demultiplexing of spatial/wavelength/polarization modes is desired by a compact device with a minimal footprint.

Acknowledgements

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