論 文 の 内 容 の 要 旨

論文題目　Integrated Optical Unitary Converter Based on Multi-Plane Light Conversion
（多面光変換法に基づく集積光ユニタリ変換器に関する研究）

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An integrated optical unitary converter (OUC), which can realize arbitrary $N \times N$ unitary transformation on chip, is promising for widespread applications in various areas, such as optical communication, quantum information processing, and optical neural networks. For example, mode-division-multiplexing (MDM) is the key technology to realize higher-capacity optical communication systems, but the mode coupling effect that occurs inside few-mode fibers (FMFs) scrambles all the signals that are originally carried by different modes of the FMF. In this case, an OUC can be employed to compensate for the mode coupling effect, thus functioning as an all-optical multi-input-multi-output (MIMO) mode demultiplexer. Compared with the MIMO mode demultiplexing by digital signal processing (DSP), all-optical demultiplexing offers unique advantages, such as bit-rate-independent operation and low power consumption. Besides optical communication, with the revival of optical computing, especially in artificial neural networks, OUCs are attracting emerging interest for realizing deep learning processors with significantly less power consumption. Deep learning relies heavily on matrix-vector multiplication. Although an OUC can only generate unitary matrices, non-unitary matrices can also be generated using two OUCs along with a variable optical attenuator array, based on singular value decomposition (SVD). Direct matrix-vector multiplication in the optical domain, enabled by this scheme, can theoretically reduce energy consumption to a great extent.

To date, integrated $N \times N$ OUCs have been demonstrated on silica, InP, SiN, and silicon-on-insulator (SOI) platforms, using cascaded 2×2 Mach-Zehnder interferometers (MZIs) based on Reck's scheme or its variation. However, all these existing OUCs suffer two common problems: 1. the operation bandwidths are limited to less than 10 nm, which prevent their deployment into wavelength-division-multiplexing (WDM) optical communication systems; 2. the device performances are sensitive to fabrication errors, due to sensitive 50:50 optical splitters. On the other hand, the multi-plane light conversion (MPLC) is a free-space scheme that can realize reconfigurable continuous unitary transformations. The symmetric and robust nature of MPLC brings the hope to solve the problems in existing integrated OUCs. In this thesis, I propose and demonstrate novel integrated OUCs based on MPLC.

Chapter 1 introduces the background of integrated OUCs and explains the problems of previous works.

Chapter 2 first introduces the basics of photonic integrated circuits (PICs), including the analysis of optical waveguides, several simulation methods, and waveguide-based components. The waveguide analysis gives the basic properties of optical waveguides, especially the concept of polarization and mode. The finite difference method (FDM) is suitable for complicated waveguide analysis and the eigenmode expansion method (EME) is suitable for simulating passive photonic devices with periodic structures. The operation principles of MMI coupler, directional coupler, phase shifter, Mach-Zehnder interferometer (MZI), and spot-size converter are explained in detail. Next, the theory of MPLC is introduced. Any unitary transformation can be realized by a finite sequence of phase plate and Fourier transformation.

Chapter 3 first presents the proposal of a novel integrated OUC structure for wideband operations, which consists of cascaded stages of multimode interference (MMI) couplers and phase shifter arrays. From the numerical analysis, I show the ability of this device to implement reconfigurable $N \times N$ unitary conversions with high fidelities. By using more than N stages, desired unitary matrices are realized with mean square errors (MSEs) smaller than -20 dB for all tested cases. Moreover, I show an example of applying the device to 16-mode unscrambling in MDM transmission systems with a modal crosstalk less than -24 dB. Next, I experimentally demonstrate a 3×3 OUC on a compact silicon chip based on the proposed structure. By optimizing the phase shifters with a custom-designed printed circuit board (PCB), reconfigurable 3-mode demultiplexing is realized with a wavelength-dependent loss of less than 3 dB and a modal crosstalk of less than -10 dB over 23-nm (1542.5~1565.5 nm) wavelength range. Besides, error-free demultiplexing of 40-Gbps non-return-to-zero (NRZ) signals is successfully demonstrated. This is the first experimental demonstration of an integrated OUC based on MPLC.

Chapter 4 first presents the proposal a novel integrated OUC that is robust to fabrication errors, which consists of cascaded stages of multiport directional couplers (DCs) and phase shifter arrays. Similarly, from numerical analysis, I show the ability of this device to implement reconfigurable $N \times N$ unitary conversions with high fidelities. The robustness is attributed to the inherent property of the multiport DC because the port-dependent loss is nearly eliminated. The numerical analysis further shows that the device performance is related to the entropy of coupling of the multiport DC. We can find a wide range of waveguide gap (G) and length (L) of the multiport DC that can yield a relatively good device performance. Next, I experimentally demonstrate a 4×4 integrated OUC on the SOI platform based on the proposed structure. By optimizing all the phase shifters with the PCB, reconfigurable all-optical 4-mode demultiplexing is realized with a modal crosstalk of less than -10.5 dB at the 1550-nm wavelength. The relatively large modal crosstalk results from the limitation of the driver circuit, which can drive each phase shifter only up to 1.3π. Error-free demultiplexing of 40 Gbps NRZ signals is also demonstrated.

Chapter 5 presents the design and preliminary characterization results of a 10×10 OUC using multiport DCs, and compares the devices in this work with previous demonstrations. While all other works are based on the MZI structure, the OUCs demonstrated in this work present different methods that have unique advantages, such as the wide operation bandwidth or robustness against fabrication errors. What's more, the 10×10 OUC in this work is the largest-scale device that obeys the standard N×N structure.

Chapter 6 concludes this thesis and discusses the future prospect of this work. Further efforts should be put into finding the rigorous proof that the proposed integrated OUC structures are universal to arbitrary unitary transformation, although the numerical results indicate that they can realize a large number of desired unitary transformation with sufficiently-high fidelities. In addition, the device performance, optimization time, power consumption, and device size should be further improved.