Heterogeneous integrated fiber-chip system enabling 192-channel and 20-Tbit/s multi-dimensional optical signal transmission and processing

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Abstract: We demonstrate a heterogeneous integrated multi-dimensional fiber-chip system using few-mode fiber and 2D/3D integrated chips. By carrying a 56 Gbaud QPSK signal, the system with 192 mode/polarization/wavelength channels implements 20-Tb/s optical signal transmission and processing.

1. Introduction

Optical interconnection and processing are of great significance for modern high-speed and high-capacity communication networks and promote the continuous progress of modern information technology [1]. The rapid development of fiber optics in the past few decades has demonstrated its superior ability to transmit optical signals in optical communication networks [2,3], while the integrated photonics platform provides a promising platform for flexible signal processing [4,5]. Therefore, the future development trend in modern communication networks would be to implement a whole fiber-chip system, which transmits signals by optical fiber link and processes signals by integrated on-chip networks [6]. To meet the growing capacity demand, multi-dimensional multiplexing technology has gradually attracted more and more attention [7,8]. Although significant progress has been made in fiber-optic devices and integrated devices for improving communication capacity, the fiber-chip optical interconnection and processing systems with multi-dimensional multiplexing technology still is a significant challenge. The reason is the lack of effective multimode fiber-chip couplers to address the multi-mode mismatch between fiber and waveguide in shape and size. Furthermore, the heterogeneous integration technology allows for the mixed-use of various functional small chips from different manufacturing processes, which improves yield and simplifies design/verification.

In this paper, we implement the efficient heterogeneous integrated multi-dimensional coupling between few-mode fiber (FMF) and multi-mode waveguide (MMW) by the 3D silica fs-laser writing photonic chip and 2D silicon processed by lithography, to construct a multi-dimensional (modes, polarizations, wavelengths) FMF-chip system with 192 (3×2×32) channels. Benefiting from the 3D processing capability of fs-laser writing technology, this heterogeneous integrated coupler can be extended to implement the direct coupling of higher-capacity fibers (such as multi-core few-mode fiber, OAM fiber) and silicon multimode waveguide. In addition, each channel can be flexibly processed by the 2D silicon reconfigurable optical add/drop multiplexer (ROADM) with more than 1800-unit devices. By carrying a 56 Gbaud QPSK signal, the communication system possesses an aggregate 20 Tbit/s system capacity and achieves a bit-error ratio (BER) of less than 3.8×10-3 per channel signal. To the best of our knowledge, this communication system possesses the maximum signal channels and capacity compared with reported fiber-chip data transmission and processing experiments.

2. Concept and principle

Fig. 1(a) displays the proposed heterogeneous integrated multi-dimensional FMF-chip system, which can support simultaneously mode-division multiplexing (MDM), polarization-division multiplexing (PDM) and wavelength-division multiplexing (WDM) and enable 192-channel optical signal transmission and processing. The heterogeneous integrated multi-dimensional coupling is the fundamental technology, which enables the efficient and broadband conversion between six linear polarization (LP) modes ($LP_{01}^{x/y}$, $LP_{11a}^{x/y}$, $LP_{11b}^{x/y}$) in FMF and six waveguided modes (TE_0, TE_1, TE_2, TM_0, TM_1, TM_2) in MMW, consisting of 3D silica chip and 2D silicon chip. As shown in Fig. 1(b), the 3D silica chip employs the direct edge coupling method to connect the FMF and silicon chip. When the LP modes in FMF convert into waveguide modes in MMW, the 3D silica chip is a photonic lantern mode demultiplexer with the peculiarity of polarization independence, which achieves the demultiplexing of six LP modes. Then, the fundamental modes with two polarizations in three different channels are coupled to different single-mode silicon waveguides. Finally, the on-chip high-order modes can be obtained by the cascaded asymmetric directional couplers (ADCs) mode/polarization multiplexers.

Additionally, to process optical signals, the converted six waveguide modes can be demultiplexed into six single-mode waveguides. As shown in Fig. 1(c), the array of 32 cascaded microrings in series is added behind each waveguide to achieve wavelength multiplexing and processing as a reconfigurable optical add-drop multiplexer (RODAM).

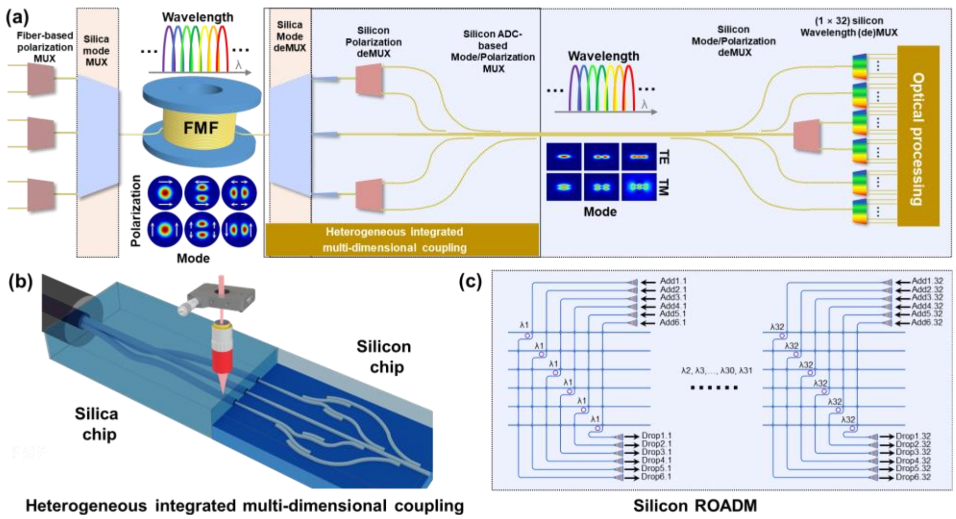

Fig. 1. (a) The concept of the heterogeneous integrated multi-dimensional fiber-chip system using FMF and 2D/3D photonic integrated chips. (b) Heterogeneous integrated multi-dimensional coupling by using 3D silica fs-laser writing photonic chip. (c) 2D silicon reconfigurable optical add/drop multiplexer (ROADM) integrated with more than 1800-unit devices. ADC: Asymmetric directional coupler; FMF: few-mode fiber; (de)MUX: (de)multiplexer.

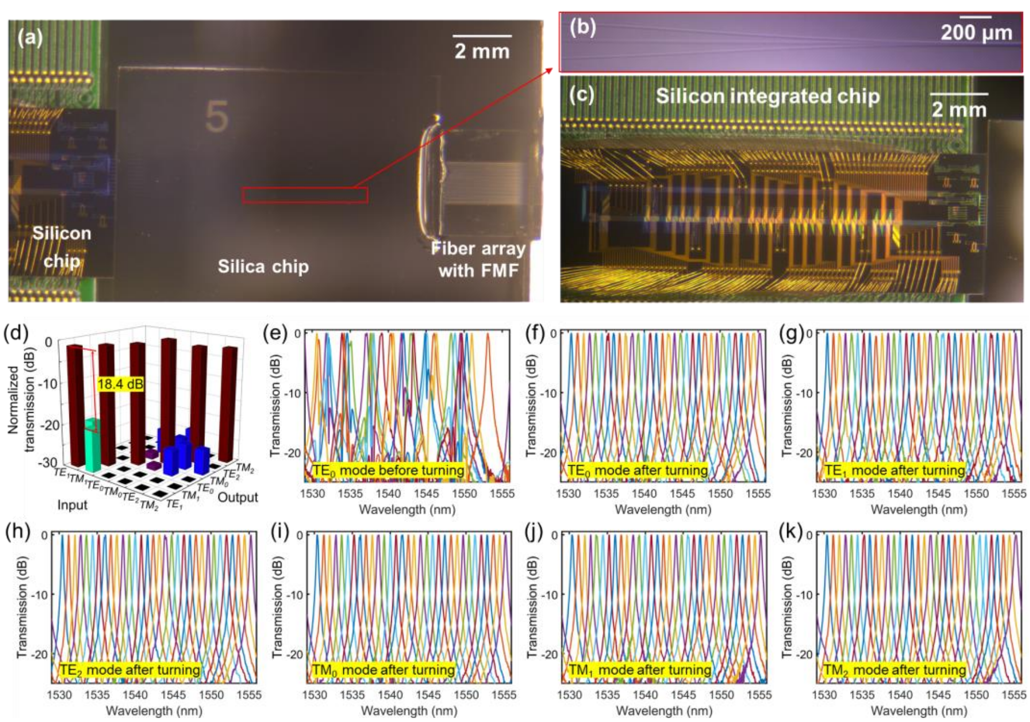

Fig. 2. (a) The microscope image and (b) an enlarged view of the fabricated silica chip. (c) The microscope image of the silicon chip. The performance of silica chip and silicon chip. (d) The measured normalized crosstalk matrix of photonic lantern mode (de)multiplexer. (e) The measured normalized transmission spectra of the silicon 32 cascaded microrings array in series before hermo-optical tuning (corresponding to the TE_0 mode). (c-h) The measured normalized transmission spectra of the silicon 32 cascaded microrings array in series after hermo-optical tuning (corresponding to the (f)TE_0, (g)TE_1, (h)TE_2, (i)TM_0, (j)TM_1, and (k)TM_2 modes).

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3. Experiments and results

3.1 Devices

Fig. 2(a) illustrates the microscope images of the heterogeneous integrated fiber-chip coupler consisting of silica chip and silicon chip. Fig. 2(a) depicts the enlarged view of the silica chip. The 3D silica chip is fabricated by the femtosecond laser fabrication technique, which can implement the (de)multiplexing of LP mode. Fig. 2(d) describes the normalized crosstalk matrix of the silica chip, which demonstrates the worst crosstalk is < -18.04 dB. Then, the polarization-insensitive single-mode couplers are utilized to connect the silica chip and silicon chip. Then, the multiple modes in MMW can be obtained by the silicon mode (de)multiplexer. Finally, the heterogeneous integrated coupler achieves the efficient conversion between the LP modes in FMF and waveguide modes in MMW.

The silicon chip is fabricated by the standard CMOS-compatible fabrication process. It is worth mentioning that over 1800-unit devices are integrated into the silicon chip. Fig. 2(e) and (f) show the measured normalized transmission spectra of the silicon 32 cascaded microrings array in series before and after thermo-optical tuning (corresponding to the TE_0 mode), which indicates the cascaded microrings array can achieve the 100-G wavelength channel spacing and the crosstalk of ~ -15 dB. The favorable performance can be obtained from other mode channels, as shown in Fig. 2(g-k).

3.2 Few-mode fiber-chip system

Fig. 3(a) - (c) displays the experimental setup of the transmitter, heterogeneous integrated FMF-chip system, and receiver. To get closer to the real communication situation, the 32 wavelengths are divided into odd and even channels, which load different 56 Gbaud QPSK signals. Fig. 3 (d) plots the BER performance for the 192 channels of the FMF-chip system, which shows that 192 channels all realize the BER of $3.8e^{-3}$. To the best of our knowledge, compared with the previous fiber-chip system, this system has the highest system capacity of 20 Tbit/s.

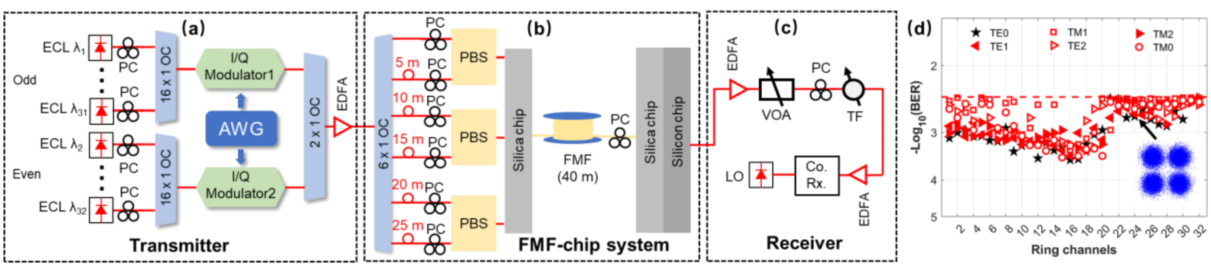

Fig. 3. (a-c) The experimental setup of (a) transmitter, (b) heterogeneous integrated multi-dimensional FMF-chip system, and (c) receiver. (d) BER performance for the 192 channels of the FMF-chip system. ECL: External Cavity Laser; PC: Polarization Controller; OC: optical coupler; AWG: Arbitrary Waveform Generator; EDFA: Erbium-Doped Fiber Amplifier; VOA: Variable Optical Attenuator; TF: tunable filter, LO: local oscillator, Co.Rx.: coherent receiver.

4. Conclusion

In summary, we demonstrate a multi-dimensional FMF-chip system based on the heterogeneous integrated coupler using 2D/3D photonic integrated chips. The heterogeneous integrated coupler can convert the multi-mode coupling to multiple single-mode coupling. Therefore, the heterogeneous integrated coupler can be extended to enable the direct coupling of higher-capacity fibers and silicon multimode waveguide. By carrying 56-Gbaud QPSK signals, the FMF-chip system with 192 channels achieves an ultra-high throughput of 20 Tb/s. Such an FMF-chip system has refreshed the best level of the fiber-chip system in communication capacity and provides important support for building more complex, larger-scale, larger-capacity, and multi-fiber optical communication networks.

5. Funding

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6. References

[1] C. DeCusatis et al., “Optical Interconnect Networks for Data Communications,” J. Light. Technol. **32**, 544-552 (2014).
[2] J. Wang et al., “Orbital Angular Momentum in Fibers,” J. Light. Technol. **41**, 1934-1962 (2023).
[3] J. Wang et al., “Orbital angular momentum communications based on standard multi-mode fiber,” APL Photonics **6**, 060804 (2021).
[4] W. Zhang et al., “Photonic integrated field-programmable disk array signal processor,” Nat. Commun. **11**, 406 (2020).
[5] X. Cao al., “Mesh-Structure-Enabled Programmable Multitask Photonic Signal Processor on a Silicon Chip,” ACS Photonics **7**, 2658-2675 (2020).
[6] K. Li et al., “Handling mode and polarization in fiber by fs-laser inscribed (de) multiplexer and silicon switch array,” PhotoniX **4**, 14 (2023).
[7] J. W et al., “Terabit free-space data transmission employing orbital angular momentum multiplexing,” Nat. Photonics **6**, 488-496 (2012).
[8] D. D et al., “10-Channel Mode (de)multiplexer with Dual Polarizations,” Laser Photonics Rev. **12**, 1700109 (2018).