Fan-in/Fan-out for Heterogeneous 19-core Fibers Based on Metasurfaces with Nonuniform Phase Plates

Yang Wang[1], Xutao Wang[1], Zhiqun Yang[1*], Yaping Liu[1*], Zhanhua Huang[1], and Lin Zhang[1,2*]

[1]Key Laboratory of Opto-electronic Information Technology of Ministry of Education and Tianjin Key Laboratory of Integrated Opto-electronics Technologies and Devices, School of Precision Instruments and Opto-electronics Engineering, Tianjin University, Tianjin, 300072, China

[2]Peng Cheng Laboratory, Shenzhen 518038, China

**Corresponding authors: yangzhiqun@tju.edu.cn, liuyp@tju.edu.cn, lin_zhang@tju.edu.cn*

Abstract: We propose a metasurface-based fan-in/fan-out device for heterogeneous 19-core fibers over the whole C band. Our results indicate that an average insertion loss of 0.9 dB and the maximum crosstalk of -25.5 dB can be achieved at 1550 nm. © 2023 The Author(s)

1. Introduction

With the explosive growth in demand for communication capacity, space-division multiplexing (SDM) becomes a promising technology to cope with the increasing data traffic. In SDM systems, fan-in/fan-out (FIFO) devices with a low insertion loss (IL), high core counts, and broad bandwidth are required to accomplish the accurate light coupling between multicore fibers (MCFs) and ordinary single-mode fibers (SMFs). A few kinds of FIFO devices have been proposed and fabricated, including tapering fiber bundles [1], 3D waveguides [2], free-space coupling components [3,4], and so on. Tapered-fiber FIFO is typically featured by a low IL, while the processing technology restricts its core counts. Besides, the free-space FIFO would be significantly bulky and unstable as the number of fiber cores increases. The 3D-waveguide-based FIFO could support respectively larger core counts, but the IL is higher.

In recent years, heterogeneous MCFs have attracted increasingly more interest, and a single piece of MCF with multiple heterogeneous cores may find critical applications in smart cities and unmanned scenarios for simultaneous external sensing and data signaling, including digital or analog channels. It is noted that the tapering fiber bundle approach is extremely difficult in practice, while the two other FIFO technologies also become unrealistic. Multi-plane light conversion (MPLC) has been reported as a multiplexer for coupling from SMF array to 7-core 5-mode fiber [6], and it holds a great potential to achieve FIFOs. Nevertheless, conventional MPLC devices are still expensive and require sophisticated manufacturing. In contrast, metasurface-based devices leveraging CMOS-compatible high-volume semiconductor processing technologies are very attractive and have not been explored for FIFO applications.

Here, we propose a metasurface-based MPLC device to realize FIFOs for heterogeneous 19-core fibers. By measuring each pixel on fabricated metasurfaces using scanning electron microscope, we obtain experimentally accessible metasurface elements' properties. Using those data, we find that the average IL of the proposed metasurface FIFO can be as low as 0.9 dB with the maximum crosstalk of -25.5 dB at 1550 nm in our design. Over the C-band, the IL and crosstalk are better than 2.8 dB and -19.56 dB, respectively. Moreover, the concept of multi-scale phase plates [7] is used to increase flexibility of phase mask size towards the MCF side, so called nonuniform-phase-plate MPLC (NPP-MPLC).

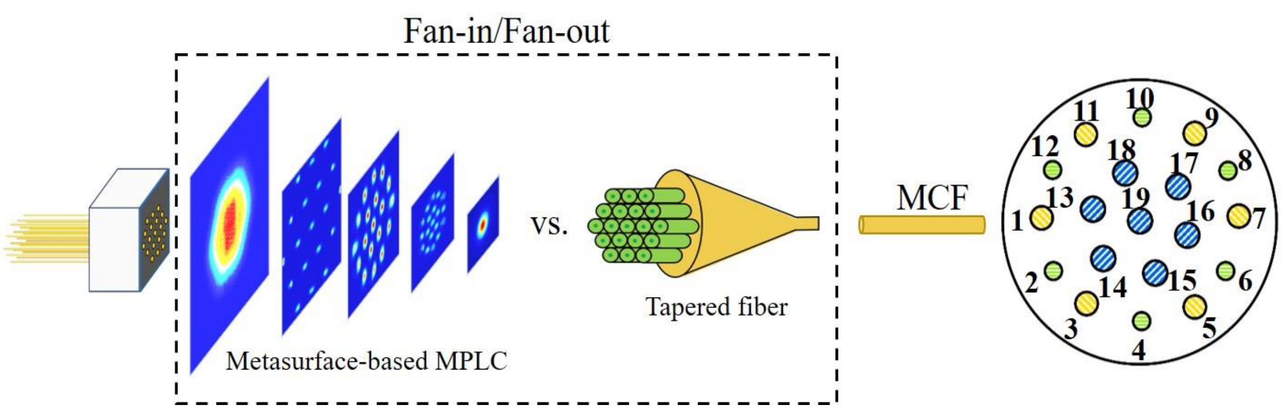

Fig. 1. The proposed metasurface-based FIFO vs. tapered fiber bundle FIFO, for heterogeneous 19-core fibers with three types of core radices, i.e., 3 μm (green, outside), 12 μm (yellow, outside), and 12.5 μm (bule, inside) for both sensing and data signaling applications. The metasurface-based FIFO with NPPs can deal with various fiber configurations without additional difficulty.

2. Principle of the metasurface-based FIFO with NPPs

The scheme of the proposed FIFO and the tapered FIFO for the heterogeneous 19-core fiber is shown in Fig. 1. The NPP-metasurface-based FIFO consists of 5 phase masks. Since the transverse area of the 19-core fiber is 1/59 of the SMF array, the required size of the phase plates becomes smaller and smaller along the transmission direction to the 19-core fiber side, and the phase masks have adaptive variable resolutions of 1100×1100, 1000×1000, 900×900, 800×800, and 700×700, with one pixel of 2×2 μm^2 for its low fabrication cost. The mode field diameter (MFD) of the SMF and the array pitch are 10 μm and 180 μm, respectively. The 19 SMF pigtails are arranged in a regular hexagon type. The distances between the single-mode array and the first mask, adjacent masks, the mask and the heterogeneous 19-core fiber are 5 mm, 15 mm, and 5 mm, respectively. It should be noted that the heterogeneous 19-core fiber has three types of functional cores with the MFDs of 6 μm, 24 μm, and 25 μm, and the core pitch is 56 μm. The phase shift of each pixel of the 5 phase plates is set to an arbitrary value between 0 and 2π, and the phase distribution of each mask can be obtained by the angular spectrum algorithm, that is, a modified wavefront matching method.

3. Design of the NPP-metasurface-based FIFO

The NPP-MPLC-based FIFO possess the characteristic of reversibility, whether the light is input from the SMF array or the heterogeneous 19-core fiber. Taking the fan-in function of this device as an example, the amplitude distribution of the input and output light is shown in Fig. 2(a), and the Fig. 2(b) shows the amplitude and the phase distribution of each mask. The main function of the first three phase masks is to change the light arrangement, and the 4^{th} and 5^{th} phase masks are mainly focused on adjusting the MFD of each channel to match the heterogeneous 19-core fiber.

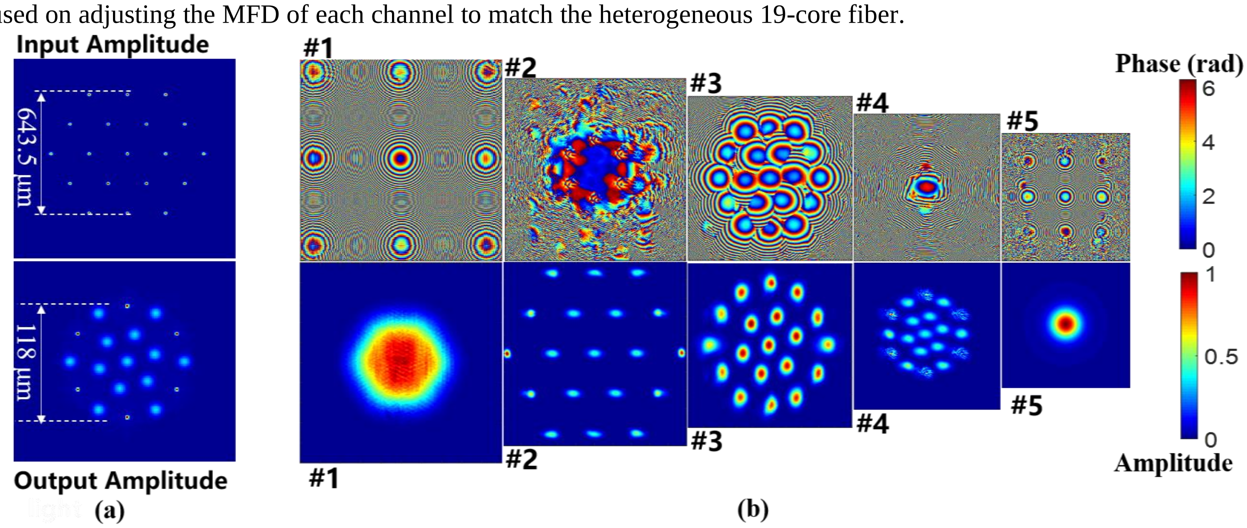

Fig. 2. (a) The amplitude distribution of the input and output light, (b) the amplitude distributions (bottom images) and phase profiles (top images) on plate 1 to plate 5.

Figure 3(a) and (b) show the IL and crosstalk at the center wavelength of 1550 nm. It has shown that the inner cores of the FIFO device corresponding to case 13 to 19 in Fig. 3(a) have larger losses than the outer cores. The center core (case 19) has the largest loss of 1.13 dB, and the average IL is 0.9 dB.

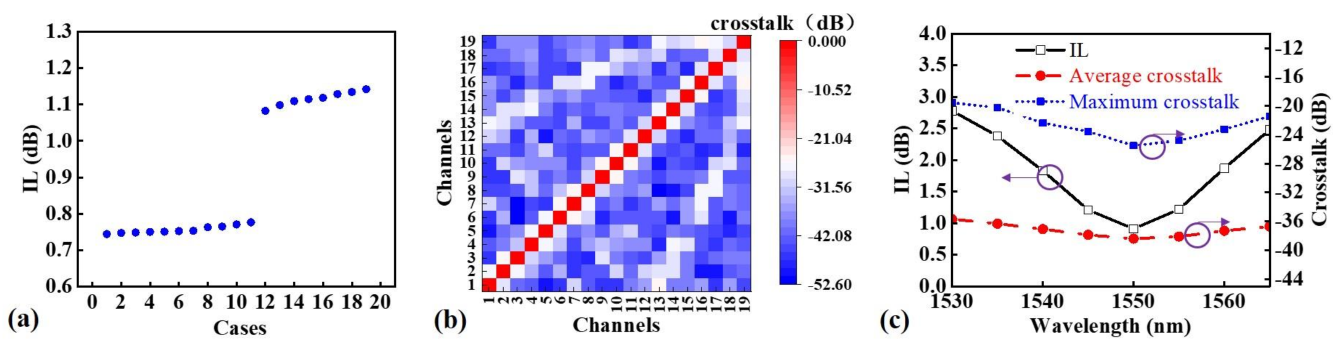

Fig. 3. (a) Insertion loss (IL) and (b) crosstalk of each core channel at 1550 nm, the average IL and maximum crosstalk are 0.9 dB and -25.5 dB, respectively, (c) The IL and crosstalk of the proposed metasurface-based FIFO over the C-band.

The crosstalk values between different cores are shown in Fig. 3(b). The adjacent cores have larger crosstalk than nonadjacent cores, and the inner cores exhibit lower crosstalk. The maximum crosstalk of the FIFO device is -25.5 dB, while the average value is -38.4 dB. We also demonstrate the IL and crosstalk characteristics of our proposed device across the C-band shown in Fig. 3(c), the maximum IL and crosstalk are 2.78 dB and -19.96 dB respectively, illustrating the feasibility in the wideband range.

The phase masks could be realized by metasurface, and we have designed 800-nm-high amorphous silicon pillars placed on the silica substrate. The refractive indexes of silicon (Si) and Glass (SiO_2) come from the ellipsometer measured at the C-band, and we have found 15 pillars whose phase shift is in $[0, 2\pi)$ with high transmittance. Images of the fabricated metasurface are taken by the scanning electron microscope (SEM) shown in Fig. 4(a), while the phase shift and the transmittance of designed and fabricated pillars are shown in Fig. 4(b). Figure 4(c) shows the experimental errors of fabrication are within ±7 nm, which is obviously lower than the designed metasurface tolerant error of ±12 nm. We plan to use those pillars to rearrangement for the phase masks of the FIFO device.

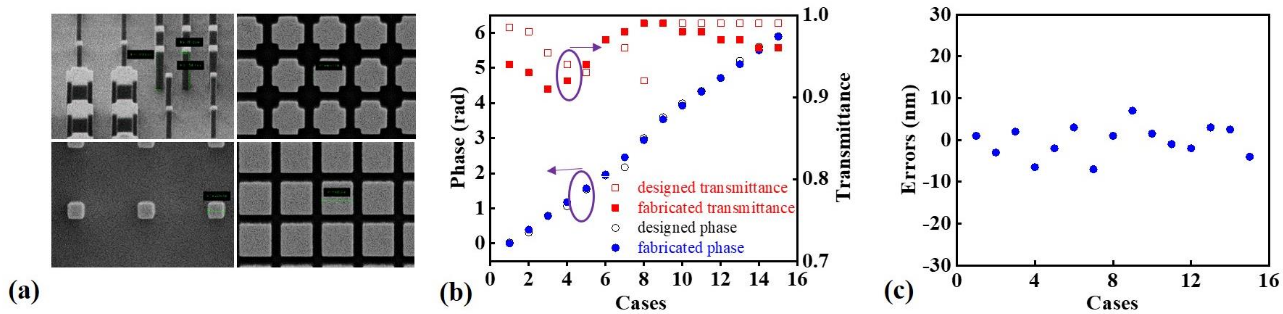

Fig. 4. (a) The scanning electron microscope (SEM) images of the Si pillars on fabricated metasurfaces, (b) the phase shift and transmittance of designed and fabricated pillars according to the lengths measured by the SEM, (c) the experimentally measured dimension errors between the designed and fabricated pillars.

4. Conclusion

We propose a metasurface-based nonuniform-phase-plate MPLC to realize fan-in/fan-out for the heterogeneous 19-core fiber. Simulation results show that the average IL is 0.9 dB, and the maximum crosstalk is -25.5 dB at 1550 nm. The performance over the C-band also remains stable, where ILs are <2.71 dB and the crosstalks are <-19.6 dB.

5. Acknowledgements

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