3D Waveguide Fan-in Fan-out Devices for Few-mode Multi-core Fibers

line 1: 1st Yanan Zhong
line 2: *Nanophotonics Research Center, Institute of Microscale Optoelectronics & State Key Laboratory of Radio Frequency Heterogeneous Integration*
line 3:*Shenzhen University*
line 4: Shenzhen, China
line 5:2110496046@email.szu.edu.cn

line 1: 2nd Aru Kong
line 2: *Nanophotonics Research Center, Institute of Microscale Optoelectronics & State Key Laboratory of Radio Frequency Heterogeneous Integration*
line 3:*Shenzhen University*
line 4: Shenzhen, China
line 5:kongaru2020@email.szu.edu.cn

line 1: 3rd Ting Lei
line 2: *Nanophotonics Research Center, Institute of Microscale Optoelectronics & State Key Laboratory of Radio Frequency Heterogeneous Integration*
line 3:*Shenzhen University*
line 4: Shenzhen, China
line 5:leiting@szu.edu.cn

line 1: 4th Xiaocong Yuan
line 2: *Nanophotonics Research Center, Institute of Microscale Optoelectronics & State Key Laboratory of Radio Frequency Heterogeneous Integration*
line 3:*Shenzhen University*
line 4: Shenzhen, China
line 5:xcyuan@szu.edu.cn

***Abstract*—Space division multiplexing technology based on few-mode multi-core fibers (FM-MCFs) is one of the effective methods to break the bottleneck of current optical communication transmission capacity. We designed and fabricated a 3D optical waveguide fan-in fan-out (FIFO) device using femtosecond laser direct writing technology, and it realized the optical coupling between a single few-mode 7-core fiber and 1×7 few-mode fiber arrays. The device supports LP01, LP11, LP21 mode transmission at a wavelength of 1310nm.**

Keywords—few-mode multi-core fiber, space division multiplexing, 3D waveguide, femtosecond laser direct writing

I. INTRODUCTION

With the rapid growth of internet capacity in optical communication systems, the space division multiplexing (SDM) technology based on FM-MCF is one of the most effective approaches to break the capacity limitations of single-mode fiber communication. Recently, Soma et al. built the first dense wave-division multiplexing/SDM communication system in 2018 using 19-mode, 6-core few-mode multicore fiber. They conducted communication experiments of 64-QAM and 16-QAM signals with a transmission capacity of 10.16 Pbit/s and a transmission rate of 89.1 Tbit/s for a single spatial channel [1]. Rademacher et al. in 2020 achieved a transmission rate of 10.66 Pbit/s and an average rate of 93.5 Tbit/s per spatial channel using 13 km of 3-mode, 38-core few-mode multicore fiber [2]. The few-mode multicore fiber transmission system has great advantages in future high-capacity transmission systems. However, based on the existing optical network system, we need to consider how to couple the few-mode multicore fibers with the precision-aligned few-mode fiber arrays.

Due to the different structure of the fibers, we need to use FIFO devices to realize the optical coupling between a single FM-MCF and multiple few-mode fibers. In recent years, several coupling methods have been proposed for FM-MCFs, such as free-space coupling [3], fused tapers [4], and 3D waveguide devices [5-7]. The emerging 3D laser direct writing technology uses femtosecond lasers to induce modifications in transparent materials, then the refractive index increases at the laser focus to form an optical channel. This technique offers great flexibility in the choice of substrate material, geometry of the mode field profile and configuration of the three-dimensional (3D) optical path, offering the possibility of fabricate integrated FIFO 3D optical waveguide devices. In order to satisfy the effective transmission of higher-order modes within the waveguide, we need to precisely control the effective refractive index difference between the waveguide and the cladding [5].

In this paper, we designed and fabricated a FIFO device for a FM-MCFs system. It supports LP01, LP11, LP21 mode transmission at a wavelength of 1310nm. One side of the waveguide is a 1x7 one-dimensional waveguide array with a pitch of 127μm, and the other side is seven-core distribution matched with a few-mode seven-core fiber.

II. DESIGN AND FABRICATION OF 3D OPTICAL WAVEGUIDE

Fig.1(a) shows the arrangement structure of a FM-MCF. There are six cores surrounding the center cores with a radius of 42μm and a separation angle of 60°. Fig.1(b) shows the bending convergence process of the 3D waveguide, the one-dimensional waveguide structure is gradually bent to form a seven-core structure on the other side of the waveguide, which matches the few-mode seven-core fiber structure as shown in Fig.1(a). In order to reduce the bending loss and mode leakage, the bending of the waveguide is optimized by the equation (1). Where L is the waveguide length, h is the waveguide bending height, and θ is the angle between the waveguide height and z-axis.

$$\begin{cases} y = \dfrac{6h\sin\theta}{L^5}x^5 - \dfrac{15h\sin\theta}{L^4}x^4 + \dfrac{10h\sin\theta}{L^3}x^3 \\ z = \dfrac{6h\cos\theta}{L^5}x^5 - \dfrac{15h\cos\theta}{L^4}x^4 + \dfrac{10h\cos\theta}{L^3}x^3 \end{cases} \qquad (1)$$

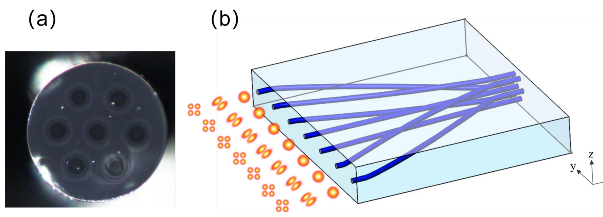

Fig. 1. FM-MCF (a) and 3D waveguide device (b).

We used Corning glass (Eagle XG) as the waveguide substrate, with the waveguide length of 17 mm and the waveguide diameter of 16.5μm for numerical simulations. Fig.2 shows that the transmission efficiencies of LP11 and LP21 modes are close to 1 and stable when the effective refractive index difference is larger than 0.0039. The calculated mode losses and coupling losses are all less than 1dB. Then, we choose a femtosecond laser with a wavelength of 1030 nm, a pulse width of 180 fs, a single pulse energy of 200 nJ, and a repetition frequency of 200 kHz to fabricate the 3D optical waveguide. The sample is moved along the curved structure of (1), and the objective lens (40x, NA=0.75) is used to focus into the sample depth of 140 μm. The refractive index difference between the waveguide and the surrounding material is optimized by controlling the parameters of scanning power, scanning times to meet the transmission requirements of the higher-order LP mode.

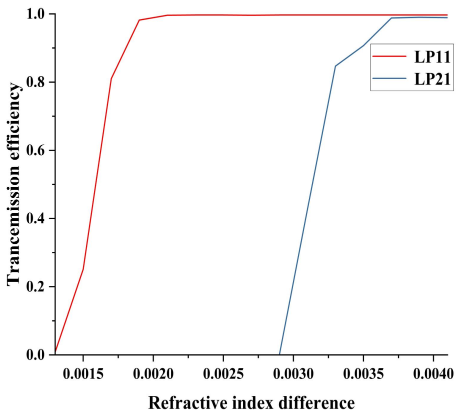

Fig. 2 Numerically simulated LP modes transmission efficiency with different effective refractive index differences.

III. Results and Discussion

In the experiments, we demonstrated the multiplexing and demultiplexing of the few-mode seven-core fiber via 3D waveguide devices. As shown in Fig. 3(a), LP modes were coupled to the one-dimensional waveguide array through the few-mode fiber array, then coupled into the FM-MCF after waveguide transmission. The distribution of the light beam is consistent with the core distribution of the FM-MCF. After the transmission of the FM-MCF, we demultiplexed through another 3D waveguide device. The multiple LP modes were generated by multi-plane light conversion (MPLC) mode multiplexer at 1310nm wavelength. The modes are transmitted coaxially and coupled into the few-mode fiber using gradient-lens. Fig.3(b) shows a picture of the MPLC device. Fig.3(c) shows a picture of few-mode fiber array and waveguide.

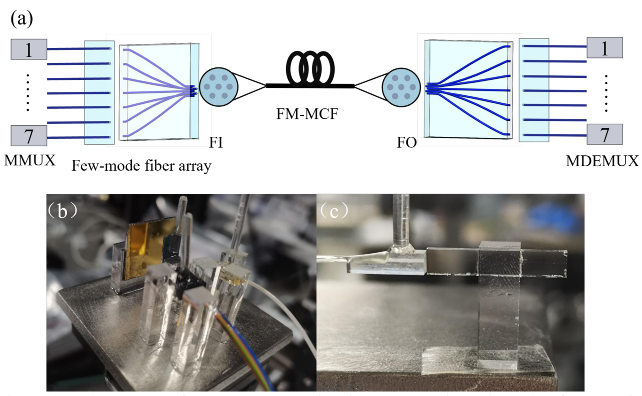

Fig. 3 (a) The setup of SDM communication system based on the few-mode seven-core fiber. (b) The 1310nm mode multiplexer. (c) Schematic of 3D waveguide coupling.

Due to the limitation of the number of mode multiplexers, the channels were tested separately. We use an objective lens at the other end of the waveguide to focus and a CCD to capture the output mode field of the waveguide. The output mode field of the 3D waveguide device is shown in Fig.4. Seven cores of the waveguide can support LP01, LP11, LP21 mode transmission at a wavelength of 1310nm. The insert losses of the LP01 and LP11 modes from the few-mode fiber array to the waveguide are less than 2dB and 3dB respectively. Due to the higher refractive index difference required for the transmission of higher-order LP mode, the insert losses of LP21 mode are less than 6dB. We need to further optimize the waveguide.

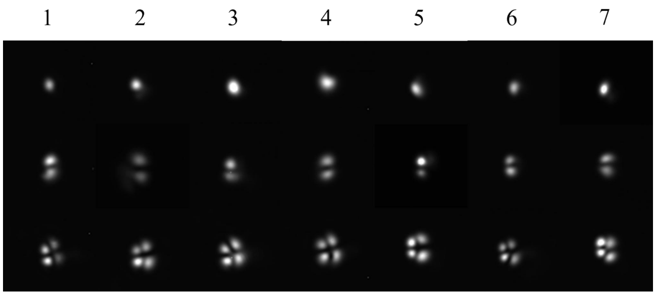

Fig. 4 Experimental intensity profiles of the LP01, LP11, LP21.

IV. Conclusion

We designed and fabricated an integrated 3D optical waveguide FIFO device using femtosecond laser direct writing technology. The device supports LP01, LP11, LP21 mode transmission at a wavelength of 1310nm, which is an indispensable device for connecting few-mode fibers and FM-MCFs.

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