Design and Fabrication of 6-Mode 7-Core Fiber Fan-in/Fan-out Device Using Multimode Fiber

Yuanhui Shao
Wuhan National Lab for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology
Wuhan, China
m202072293@hust.edu.cn

Haoze Du
Wuhan National Lab for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology
Wuhan, China
d202180843@hust.edu.cn

Fengming Zhang
Wuhan National Lab for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology
Wuhan, China
d202280959@hust.edu.cn

Zhuyixiao Liu
Wuhan National Lab for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology
Wuhan, China
d202280963@hust.edu.cn

Senyu Zhang
Wuhan National Lab for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology
Wuhan, China
senyuzhang@hust.edu.cn

Ming Tang*
Wuhan National Lab for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology
Wuhan, China
tangming@mail.hust.edu.cn

***Abstract*—We have achieved a low-cost fan-in/fan-out device for 6-mode 7-core fibers based on OM3 multimode fiber. Through simulation calculations and experimental verification, the fan-in/fan-out device has a maximum insertion loss of 0.73dB and an average insertion loss of 0.47dB at the fundamental mode of 1550nm.**

Keywords—multi-mode fibers, 6-mode 7-core fibers, fan-in/fan-out device

I. Introduction

As a promising medium candidate to overcome the capacity crunch over single-mode fiber (SMF), multifarious specialty optical fibers based on SDM technology, like multi-core fibers (MCF), few-mode fibers (FMF), and few-mode multi-core fibers (FM-MCF) have been demonstrated and investigated in many applications [1-4].

In spatial division multiplexing (SDM) systems consisting of MCF, fused tapered type Fan-in/Fan-out (Fi/Fo) devices are generally used to realize optical interconnection between MCF and SMF or few-mode fiber (FMF) bundles. A fused taper type Fi/Fo device comprises a set of individual peculiarly designed fiber named "bridge fibers (BF)".The BF are inserted into a glass tube and tapered adiabatically to form a bunch of fiber bundle, which is then spliced with the multi-core fibers. Obviously, as a key component to link different kind of fibers, the structure of BF has closely correlation with optical properties of fabricated Fi/Fo devices. In order to minimize insertion loss for all modes of operation of Fi/Fo devices, the BF usually needs to be thoroughly optimized [5,6]. However, these design optimizations require significant time and cost.

In this paper, we simulated the mode field of OM3 fiber before and after tapering, and calculated their coupling losses with the standard single-mode fiber and 6-mode 7-core fiber, respectively. Based on the simulation results, we fabricated a low-loss fan-in/fan-out device for 6-mode 7-core fibers based on OM3 multimode fiber. The device has a minimum insertion loss of 0.01 dB and a maximum insertion loss of 0.73 dB at the fundamental mode of 1550 nm.

II. Simulation design of Fi/Fo device

Fig. 1(a) shows the refractive index profile of multi-mode fiber OM3. The reference refractive index n0 is 1.444, corresponding to the refractive index of pure silica at 1550 nm. Fig. 1(b) shows the end view of OM3. The cladding diameter of OM3 is 125 µm, and the core diameter of OM3 is 50 µm.

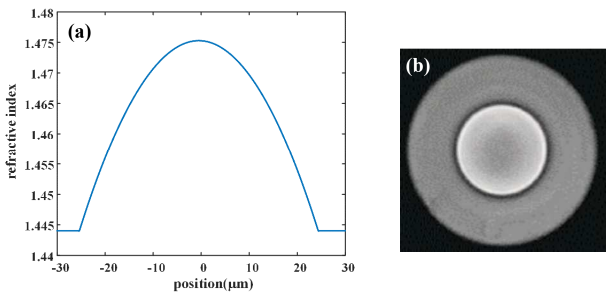

Fig. 1. (a) Refractive index profile of OM3 and (b) its end view.

Fig.2(a) shows the refractive index profile of the 6-mode 7-core fiber used in this work. Fig.2(b) shows the end view of the 6-mode 7-core fiber. Its core pitch is 42.5 µm with hexagonally-arranged silica cores for the inhibition of inter-core crosstalk.

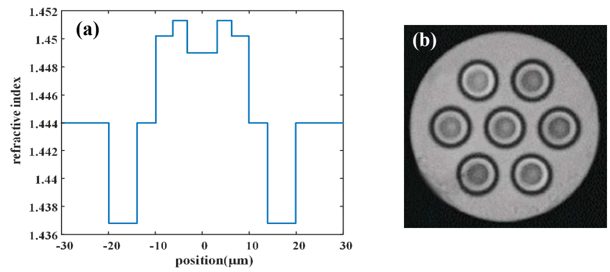

Fig. 2. (a) Refractive index profile of 6-mode 7-core fiebr and (b) its end view.

Fig. 3(a) shows the fundamental mode LP_{01} of SSMF calculated by finite element method (FEM). Fig. 3(b) shows the mode field of OM3 before tapering.

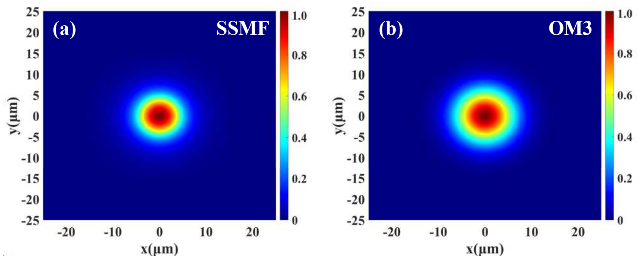

Fig. 3. Fundamental mode LP01 field of (a) SSMF and (b) OM3.

The coupling loss between SSMF and OM3 can be calculated by overlap integration of mode fields. The coupling loss of fabricated Fi/Fo device is highly dependent on the mode field mismatch of all splicing points, which can be analyzed by using the coupled mode theory. We use subscript *i* to represent the light coupled into input fiber mapping to LP mode *i*. And the $\mathbf{E}_{\mu i}$ and $\mathbf{E}_{\nu i}$ are the electric field distribution of transmitting fiber and receiving fiber, respectively, which can be obtained by physical modeling based on finite element method (FEM) with the help of commercial simulation software (COMSOL). Then the normalized power coupling efficiency of LP mode *i* between two different fibers during splicing can be calculated by the overlap integration method [7], as shown in Eq (1),

$$\eta_i = \frac{\left|\iint \mathbf{E}_{\mu i}\cdot\mathbf{E}_{\nu i}^{*}dxdy\right|^2}{\iint|\mathbf{E}_{\mu i}|^2 dxdy\iint|\mathbf{E}_{\mu i}|^2 dxdy} = \frac{\left[\iint|\mathbf{E}_{\mu i}||\mathbf{E}_{\nu i}|\,rdrd\theta\right]^2}{\iint|\mathbf{E}_{\mu i}|^2\,rdrd\theta\iint|\mathbf{E}_{\nu i}|^2\,rdrd\theta}, \quad (1)$$

where (r, θ) is the polar coordinate system at the cross section of the optical fiber, and the origin is located in the center of the core. The coupling loss of LP mode *i* at fusing points can be expressed as [8]:

$$Loss_i = -10\log_{10}(\eta_i). \quad (2)$$

Therefore, the coupling loss of fundamental mode between tapered OM3 and the 6-mode 7-core fiber can be calculated with the above overlap integration method, which is 0.181 dB at 1550 nm.

Since the core pitch of the 6-mode7-core fiber used in this work is 42.5μm, the tapering ratio is about 2.941 (125/42.5). It is assumed that the refractive index of OM3 changes uniformly after tapering. Fig. 4(a) shows the refractive index profile of OM3 and tapered OM3. Fig. 4(b) shows the transmission of Gaussian light in 20 mm OM3, where the z-axis represents the transmission distance. Gaussian light is launched into the fiber from z=0. Fig. 4(c) shows the transmission of Gaussian light in tapered 20mm OM3(TA-OM3). The core diameter is tapered from 50 μm to 8.5 μm evenly at z=5 mm to z=10 mm.

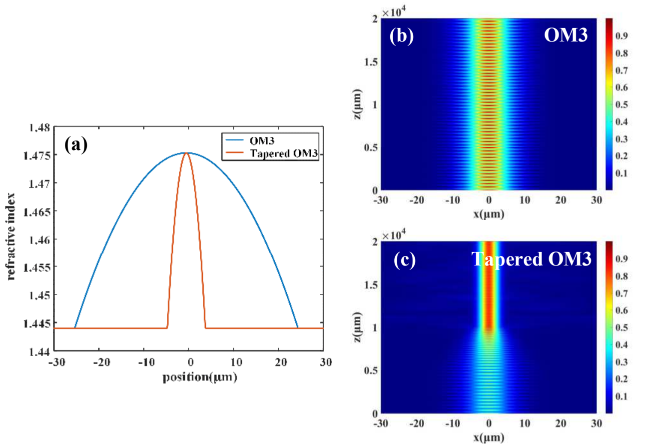

Fig. 4. (a) Refractive index profile of OM3 before and after tapering. (b) the transmission of Gaussian light in OM3 and (c) tapered OM3.

Fig. 5(a) shows the mode field of tapered OM3. Fig. 5(b) shows the mode field of the 6-mode 7-core fiber. The coupling loss between tapered OM3 and the 6-mode 7-core fiber can be calculated with the above overlap integration method, which is 0.94 dB at 1550 nm.

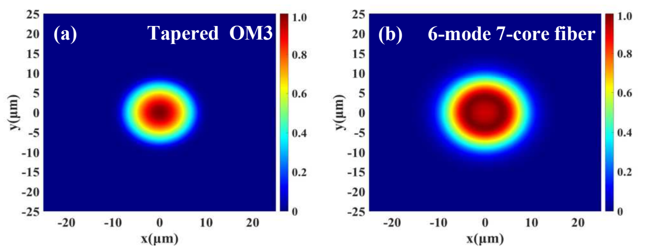

Fig. 5. Fundamental mode LP01 field of (a) tapered OM3 and (b) 6-mode 7-core fiber

III. FABRICAION AND OPTICAL PROPERTIES OF FI/FO DEVICE

The taper process was conducted by Vytran GPX3400. Fig. 6(a) shows the tapered OM3 bundle after cleaving. The average core pitch is 42.43 μm with the maximum position error about 0.05 μm. Fig. 6(b) shows the end-view of 7-core-6-mode fiber with cladding diameter of 150.0 μm. The average core pitch is 42.5 μm with the maximum position error about 0.75 μm. The splicing between tapered OM3 bundle and 6-mode 7-core fiber was conducted by specialty fiber fusion splicer (FSM-100P+, Fujikura). The angle alignment is based on self-correlation method with 0.5-degree accuracy guaranteed [9]. Fig. 6(c) and Fig. 6(d) show the fusing point of tapered OM3 bundle and 6-mode 7-core fiber before and after splicing, respectively. Fig. 6(e) shows the photograph of the metal tube packaged Fi/Fo device. The left and right part are OM3 and 6-mode 7-core fiber pigtail, respectively.

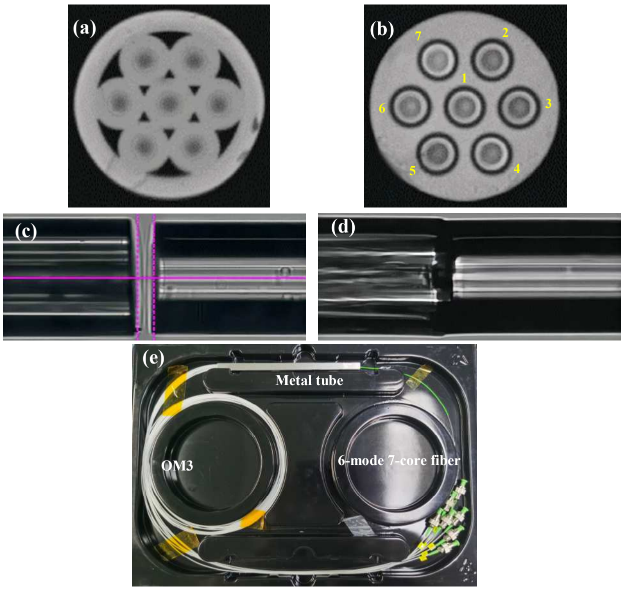

Fig. 6. End view of (a) tapered OM3 bundle and (b) 6-mode 7-core fiber. (c) Fusing point before splicing. (d) Fusing point. (e) Photograph of Fi/Fo device.

Fig. 7 shows the experimental setup for optical properties measurement of fabricated Fi/Fo device. The Fi device is The Fi/Fo device is spliced with 1 m-long 6-mode 7-core fiber. The optical source is a distributed feedback laser (DFB) with the output power of 7.15 dBm at 1550 nm. This setup can be applied to measure Fi/Fo insertion loss (IL).

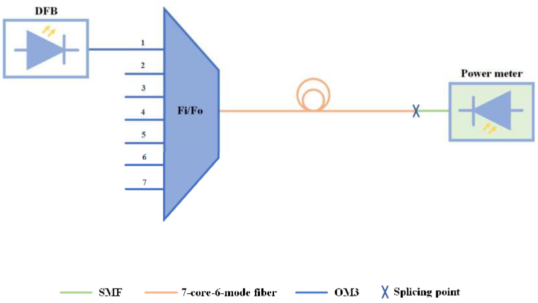

Fig. 7. Experimental setup for measuring IL of fabricated Fi/Fo device

Table 1 shows the insertion loss of Fi/Fo device at 1550 nm. The minimum and maximum insertion loss are 0.01 dB and 0.73 dB, respectively. The deviation of insertion loss should be mainly caused by imperfect cleaving of fiber bundle. Fig. 8 shows the speckle pattern of 6-mode 7-core fiber output detected by a charge coupled device (CCD). When the input at OM3 is the fundamental mode LP_{01}, 6-mode 7-core fiebr output is also mainly fundamental mode LP_{01}. There is little excitation of other modes in the fabricated Fi/Fo device

TABLE I. TOTAL IL OF ALL CHANNELS FOR FABRICATED FI/FO DEVICE MEASURED AT 1550NM

	Insertion loss (dB)						
	1	*2*	*3*	*4*	*5*	*6*	*7*
loss	0.57	0.73	0.01	0.37	0.47	0.40	0.72

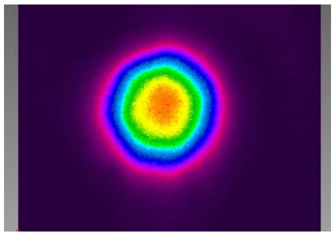

Fig. 8. Output speckle pattern of the Fi/Fo device

IV. CONCLUSIONS

In summary, we successfully fabricated a low-loss 6-mode 7-core fiber Fi/Fo device using OM3 multimode fiber. The maximum insertion loss is 0.73dB. Through simulation and experimental verification, we found that the fundamental mode field between the tapered OM3 fiber and the 6-mode 7-core fiber is matched at 1550nm. Therefore, simulation and experimentation have demonstrated that commercial OM3 fibers can be used as bridge fibers for 6-mode 7-core fiber fan-in/fan-out devices, which is a low-cost technical solution. In future work, we will further explore the losses between the tapered OM3 fiber and the higher-order modes of the 6-mode 7-core fiber.

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