Self-Written Waveguide Approach for Optical Interconnects in Multi-Core Fiber Systems

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Abstract: We present a self-written waveguide approach for efficient optical interconnects in multi-core fiber systems. This cost-effective and flexible method enables enhanced coupling between two four-core fibers, achieving 0.47 dB coupling loss and -29.61dB crosstalk. © 2024 The Author(s)

1. Introduction

In recent decades, the demand for data capacity has rapidly increased with the widespread development of fiber-to-the-home and high-speed optical networks. Conventional standard single-mode fiber, which typically operates in the C band, has a limited transmission capacity of approximately 100 Tb/s [1]. The space division multiplexing (SDM) technique has been widely adopted to enhance network capacity further. A key element for realizing SDM and meeting the growing data capacity demand in optical networks is using multi-core fiber (MCF). Connecting different MCFs is common in long-distance transmission networks to facilitate data transmission. However, challenges such as coupling loss between MCFs and inter-core crosstalk have emerged as critical issues in optical networks [2]. Inter-core crosstalk can significantly affect the quality of optical signals transmitted in neighboring fiber cores, while coupling loss between MCFs can impact the entire network [1]. Although polarization maintaining fiber patch cords are commonly employed for accurate MCF connections in engineering, they involve a complex design, costly production processes, and low alignment tolerance, resulting in high coupling loss between MCF connections due to slight offsets. Therefore, there is a pressing need for a cost-effective and flexible method to maintain low coupling loss and inter-core crosstalk between multi-core fibers.

In this paper, we demonstrate the utilization of the dye-doped-epoxy-based self-written waveguide (SWW) approach to achieve low-loss and low-crosstalk optical interconnect between two four-core single-mode fibers. The SWW approach involves creating an optical waveguide in a photo-curable epoxy by directly irradiating suitable laser light from one fiber to another. Once formed, this optical waveguide remains intact even when the light source is removed, serving as a low-loss optical link between the cores of optical fibers. We present the mechanism and fabrication process of the SWW and demonstrate an optical interconnect with a coupling loss of 0.47 dB and -29.61 dB crosstalk between two four-core fibers.

2. Mechanism of Self-Written Waveguide and Material Preparation

To form the self-written waveguide (SWW) using dye-doped epoxy and light inducement, carefully considering the appropriate combination of dye and epoxy materials is essential. For the epoxy component, we utilize MasterBond UV11-3 due to its optical transparency, a wide range of service temperatures (-50 °C to 120 °C), and relatively low viscosity of 60 centipoises. As for the dyes, we employ Rhodamine 6G (R6G), the most commonly used xanthene dye. The full compound name of R6G is (9-(o-(ethoxycarbonyl)phenyl)-6-ethylamino-2,7-dimethyl-3-xanthenylidene) ethyl ammonium chloride. R6G exhibits an absorption peak at a wavelength (λ) of approximately 530 nm. Consequently, we can employ a standard green laser source operating at 532 nm to irradiate R6G and initiate the SWW formation through photo-polymerization [3,4].

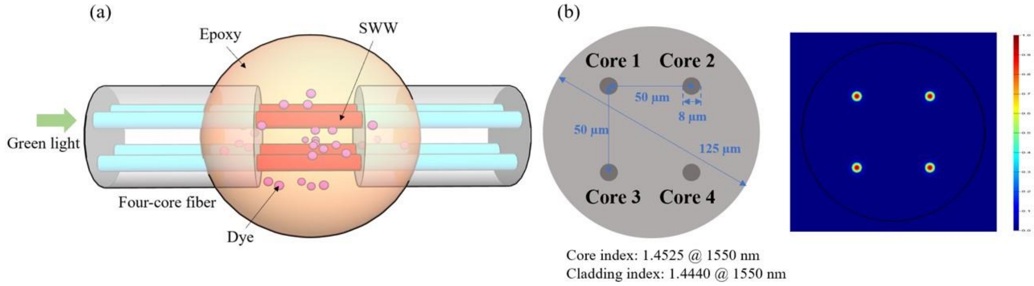

Fig. 1. (a) Schematic diagram of the SWW formed between four-core fibers; (b) Cross-sectional view and mode-field profile of the fiber.

Fig. 1(a) depicts the schematic diagram of the proposed self-written waveguide (SWW) between two four-core single-mode fibers. The four-core fiber consists of four cores with a diameter of 8 μm, arranged in a square configuration. The spacing between adjacent cores is 50 μm. Each core operates in a single-mode regime, making it suitable for high-speed and long-distance transmission. An air gap of 100 μm is maintained between the aligned four-core fibers. To initiate the SWW formation, 532 nm green light is injected into the dye-doped epoxy through one of the fiber cores. The green light is absorbed by R6G, triggering a photo-polymerization process that increases the local refractive index. As the refractive index change monotonically increases with light intensity, the region near the center of the fiber core, where the light intensity is the highest, forms a high-index SWW core that effectively confines and guides the light [5]. This self-focusing effect facilitates the continuous growth of the optical waveguide along the direction of light propagation. By launching the green light into different cores individually, SWWs can be formed between the cores of the two four-core fibers.

3. Experiment Process and Results

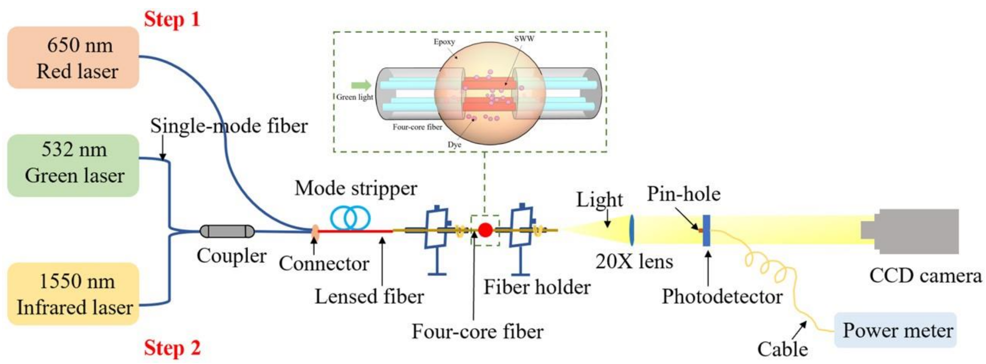

Fig. 2. Experimental setup. Initially, a CCD camera monitors the four-core fiber output light profile for optical path alignment. Subsequently, the CCD camera is replaced by a photodetector with a power meter to measure the output power at 1550 nm from the four-core fiber.

We investigate the self-written waveguide (SWW) fabrication and performance between the four-core fiber cores to demonstrate the method's potential for different multi-core fibers. As shown in Fig. 2, we launch red laser light at a wavelength of 650 nm into one core of the four-core fiber through a lensed fiber while aligning the optical path between the corresponding cores of the two four-core fibers. The output light profile of the four-core fiber is monitored using a CCD camera for precise alignment. Subsequently, stabilized green laser light at a wavelength of 532 nm and an infrared laser at a wavelength of 1550 nm are simultaneously launched into the four-core fiber via the lensed fiber using a coupler. To eliminate high-order modes of the green light that may affect SWW formation, a mode stripper is placed before the four-core fiber. The green light forms the SWW between the two four-core fibers, while the infrared laser monitors the coupling loss and crosstalk in real time. The output power at the wavelength of 1550 nm from the four-core fiber is measured using a power meter. By launching the green light into each core of the four-core fiber individually, we can form four SWWs between the cores of the two four-core fibers. Successful fabrication of SWWs between the cores of the four-core fibers is demonstrated using the experimental setup described above, with a green light power of -15.5 dBm and a dye concentration of 0.1 percentage weight (%-wt). Fig. 3 illustrates the SWW formation process and the light transmission at a wavelength of 1550 nm after the SWW is formed.

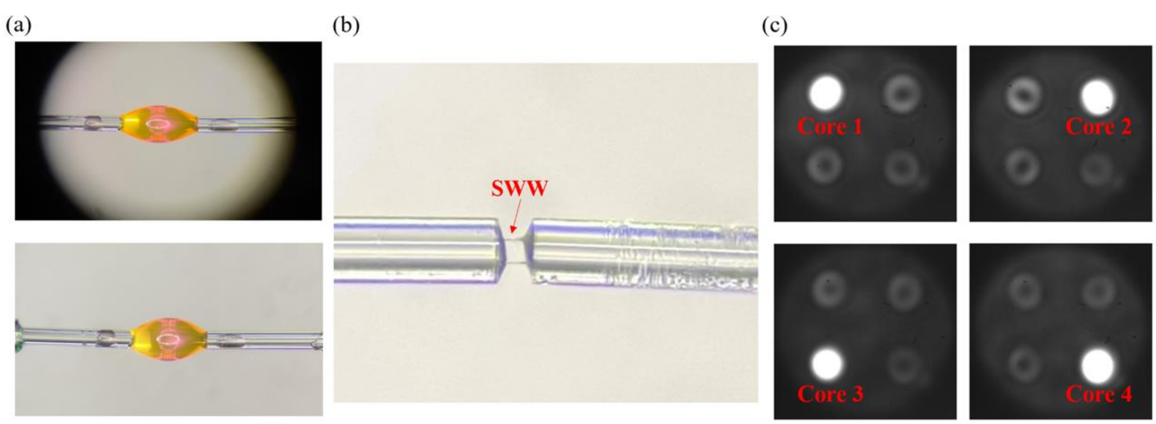

Fig. 3. (a) SWW forming process; (b) Microscopic image of the SWWs formed between two four-core fibers; (c) Output transmission mode of each core at a wavelength of 1550 nm after the SWW is formed.

Fig. 3(a) shows the growth of the SWWs along the light propagation direction when the green light is launched into the corresponding cores of the four-core fiber, ultimately connecting the cores of the two four-core fibers. We remove the surrounding epoxy using acetone to observe the formed SWWs more clearly. In Fig. 3(b), we observe waveguide-like SWW structures connecting the cores of the four-core fibers. Subsequently, we individually launch infrared light into each core of the four-core fiber to evaluate the light transmission characteristics of the SWWs at a wavelength of 1550 nm. Fig. 3(c) illustrates the output transmission mode of each core when we launch a 1550 nm light source into the corresponding cores after the SWW is formed, demonstrating effective guiding and transmission of light from one four-core fiber to another through the SWW. Additionally, we estimate the coupling loss and inter-core crosstalk between the four-core fibers based on the SWW connections, as shown in Table 1.

Table 1. Coupling Loss and Inter-Core Crosstalk Analysis of Four-Core Fibers with SWW Connections

Core	Coupling loss (dB)	Crosstalk (between adjacent cores) (dB)
Core 1	0.82	-29.26
Core 2	0.47	-29.61
Core 3	0.64	-29.44
Core 4	0.79	-29.29

To estimate the inter-core crosstalk, we launch infrared light at a wavelength of 1550 nm into one core of the four-core fiber using a lensed fiber and collect the output light using a 20X objective lens with our experimental setup. The optical power at adjacent cores is measured using a power meter to determine the crosstalk, which is found to be -30.08 dB. Furthermore, we estimate the output optical power transmitted through directly aligned four-core fibers as a reference to observe the coupling loss based on the SWW connections. According to Table 1, the SWW maintains a reliable optical interconnect between the four-core fibers, exhibiting low coupling loss and crosstalk. Moreover, our previous experimental results demonstrate a substantial lateral alignment tolerance of ± 2 μm could be achieved between fiber and waveguide with SWW connection [3].

4. Conclusion

In conclusion, the self-written waveguide approach presented in this study shows great promise for enhancing optical interconnects in multi-core fiber systems. By successfully applying the light-induced SWW method using dye-doped epoxy, we have achieved significant progress in establishing optical interconnects between two four-core single-mode fibers. This approach offers notable advantages, including ease of fabrication, low optical coupling loss and inter-core crosstalk, and high lateral alignment tolerance. Considering these advancements, our approach holds the potential to provide a cost-effective and flexible solution for reliable optical interconnects in multi-core fiber systems, with the prospect of making a significant impact in optical networks.

Acknowledgements

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