An All-Fiber Fan-Out Device for Varying Twin-Core Fiber Types

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***Abstract*—An all-fiber twin-core fiber (TCF) fan-out device is proposed and experimentally demonstrated. The device is capable of simultaneously accessing optical signals from both cores for a variety of TCF types. The device was fabricated via bi-tapering of a fiber bundle consisting of two parallel large-core multimode fibers, each of which was tapered-spliced with single mode fibers. A commercial fiber fusion splicer was used in the device fabrication process for both tapering and splicing. A series of experiments were conducted in which two different TCF types, featuring different inter-core distances, were connected to test the functionality of the proposed device. The results demonstrate successful accessing of optical signals from the two TCF cores with a low crosstalk of –38.6 dB. The proposed all-fiber TCF fan-out device could be further developed for applications in novel fiber sensors or advanced optical communication systems.**

***Index Terms*—Fiber optics and optical communications, fiber optics components, fiber optics sensors.**

I. Introduction

IN RECENT years, tremendous progress has been made in spatial-division-multiplexing (SDM) transmission due to limits in the bandwidth of a single-mode fiber (SMF) [1]–[3]. Various multi-core fibers (MCFs) and related fiber components, such as MCF lasers [4], MCF amplifiers [5], and MCF Bragg gratings [6], have been developed for SDM transmission systems. In addition, MCFs and MCF- based devices have also been developed for creating different types of sensors, such as vector bending sensors [7], [8], refractive index sensors [9], magnetic field sensors [10], strain sensors [11], flow velocity sensors [12], and accelerometers [13]. In general, accessing the core of an MCF was the prerequisite to developing a practical MCF sensing or communication systems. However, in most cases, it is difficult to spatially multiplex the light from different SMFs into MCF cores and then de-multiplex the light from MCF cores into individual SMFs. Moreover, spatial multiplexing and de-multiplexing is particularly difficult in MCFs with small inter-core distances.

Efforts have been made in recent years to fabricate high-performance MCF fan-in/fan-out devices (i.e., multiplexers/ de-multiplexers). For example, free-space optics have been adopted to create MCF multiplexers [3], [14]. Sakaguchi *et al.* designed a 19-channel MCF fan-in/fan-out device by employing a large number of fiber collimators, prisms, and lenses [3]. However, this device was too complicated and bulky for practical use. Subsequently, other types of MCF fan-in/fan-out devices were developed by inscribing optical waveguides on silica or polymer substrates with an ultrafast laser [2], [15]–[19]. Very recently, Riesen *et al.* reported on a few-mode MCF multiplexer by ultrafast laser inscription on a monolithic photonic chip and achieved a low insertion loss of 1.6–3.0 dB [19]. However, the parameters of the ultrafast laser pulses should be carefully controlled in order to obtain an optimized waveguide. Moreover, the relative high cost of an ultrafast laser limits the practical application of this method.

A more common type of MCF fan-in/fan-out device is based on adiabatically tapered photonic lanterns [1], [15]. As early as 1991, Poole and Love fabricated a twin-core fiber (TCF) connector by tapering a bundle of two SMFs, which were sealed in a silica capillary [20]. In 2006, Yuan *et al.* demonstrated effective optical coupling from one core of an SMF into different MCF cores by tapering the spliced joint [21]. In 2000, researchers from OFS Labs created a tapered 7-core MCF connector, which exhibited a low crosstalk of -37.9 dB and a low connection loss of 1.9 dB [22]. In 2012, Zhao *et al.* proposed an all-fiber TCF connector for accessing both TCF cores [23]. They used a sandwiched structure with two cascaded four-core fibers inserted between a TCF and SMFs. The simulation results projected a low connection loss of 0.056 dB, which unfortunately was not validated experimentally. Additionally, Abe *et al.* developed a physical-contact fan-in/fan-out device by arranging several

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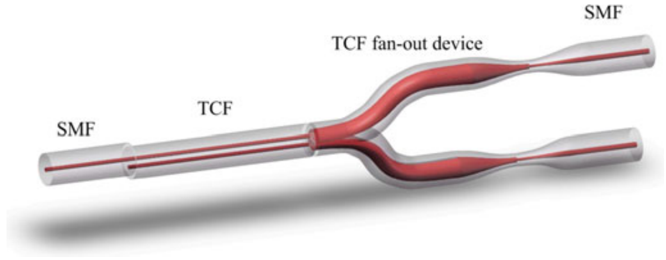

Fig. 1. A schematic of the proposed all-fiber TCF fan-out device.

small-diameter SMFs and aligning them with MCF cores. They reported a 7-core MCF fan-out device with a connection loss of 0.17 dB in 2013 and a 12-core MCF fan-in/fan-out device in 2015 [24], [25]. It should be noted that all of the above-mentioned MCF fan-in/fan-out devices were specially designed and created for specific types of MCFs. As such, a universal fan-in/ fan-out device has yet to be developed and is still in demand for different types of MCFs.

In this paper, we propose and experimentally demonstrate an all-fiber TCF fan-out device for simultaneously accessing optical signals from both cores in different TCF types. The device was fabricated via bi- tapering of a fiber bundle, consisting of two parallel large- core multimode fibers (LMFs), which were tapered-spliced with SMFs, as illustrated in Fig. 1. A commercial fiber fusion splicer was used in the device fabrication process. Experiments were conducted to test the proposed TCF fan-out device by connecting two different TCF types, with different inter-core distances. Accessing the optical signals from the two TCF cores has been successfully achieved with a low crosstalk of −38.6 dB.

II. Device Fabrication

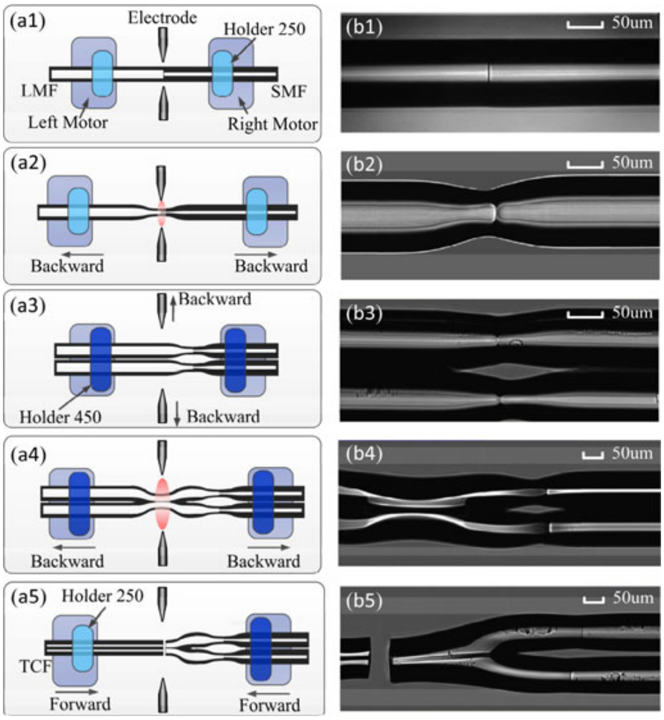

Fig. 2. (a1)–(a5) Schematic diagrams of the fabrication process for the TCF fan-out device; (b1)–(b5) corresponding side-view microscopy images of the TCF fan-out device at various fabrication steps, from step 1 to step 5, respectively.

Fig. 2 illustrates the five step fabrication process for the proposed TCF fan-out device, conducted using a commercial fiber fusion splicer (Fujikura, ARC master FSM 100P+). In the splicer, a pair of fiber holders are affixed to the left and right motors (i.e., ZL and ZR motors), respectively. The fiber holders are replaceable, in order to adapt to different fiber diameters. In contrast to traditional fusion splicers, the splicer used in our experiment has a SWEEP motor which can move the fiber (held in place by the left and right fiber holders) along the fiber axis with a maximum range of ±18 mm and a precision of 0.01 μm. The two fiber holders are placed on a translation stage which can be driven by the SWEEP motor. The splicer is also equipped with an imaging system from which microscopy images were obtained, as shown in Fig. 2(b1)–(b5). The SMF (Corning SMF-28) had a fiber core diameter of 8 μm while the LMF (Nufern MM-S105/125-22A) had a fiber core diameter of 105 μm and a high numerical aperture NA of 0.22. A cross-sectional microscopy image of these fibers is shown in Fig. 3(a), and the steps used to fabricate the TCF fan-out device in the following steps are described below.

In step 1, the LMF and SMF were fixed to the left and right fiber holders, respectively. Both fiber holders have the same type of V-groove which can clip coated fibers with a diameter of 250 μm. The LMF and SMF were then spliced together using the default arc discharge parameters for typical multimode fiber splicing. This process is shown in Fig. 2(a1) and (b1).

In step 2, the fiber holders were slowly translated away from each other using the ZL and ZR motors in manual operation mode. In this procedure, a slight tensile stress was applied to the spliced LMF and SMF. Subsequently, a continuous discharge at a standard current of 18 mA was applied, and a fiber taper was created at the LMF-SMF spliced joint. The discharge-tapering process was then repeated five times and the shape and position of the fiber taper were optimized by adjusting the relative positions of the fiber holders. Additionally, we can minimize transmission loss at the LMF-SMF spliced joint by optimizing the taper structure [21]. We repeated step 2 and fabricated another spliced LMF-SMF taper structure. This process is shown in Fig. 2(a2) and (b2).

In step 3, another pair of fiber holders, with a larger V-groove which can clip coated fibers with a diameter of 450 μm, was used to simultaneously taper the two parallel fibers. The two spliced LMF-SMF joint taper structures fabricated in step 2 were then placed side-by-side and fixed by the two fiber holders. The electrodes were aligned to the parallel fibers and moved backward ~100 μm to enlarge the heating area produced by the arc discharge. Subsequently, the two fiber holders were simultaneously moved by the SWEEP motor a distance of 500 μm to the right. This process is shown in Fig. 2(a3) and (b3).

In step 4, a bi-tapered LMF bundle was fabricated by applying an arc discharge to the parallel spliced LMF-SMF taper structures. A continuous arc discharge with a standard current

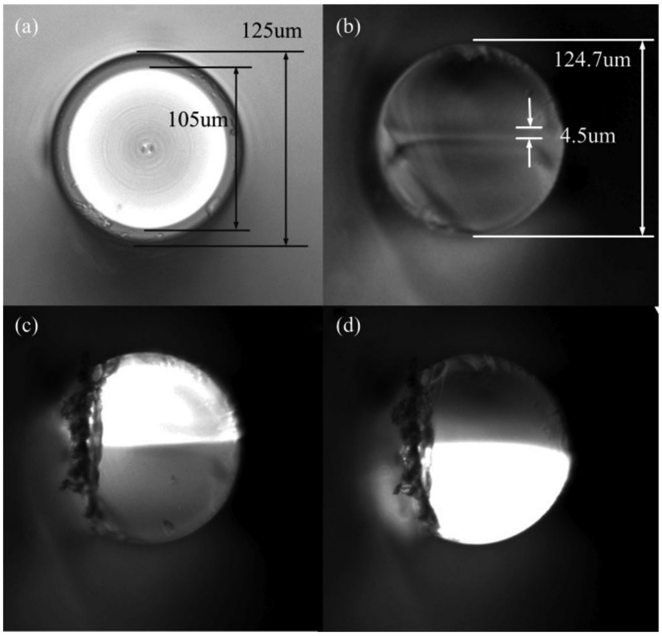

Fig. 3. Cross-sectional microscopy images of the LMF (a), the cleaved end-face of the proposed TCF fan-out device (b), the cleaved end-face of the proposed TCF splitter with light transmitted through the upper LMF branch (c), and through the lower LMF branch (d).

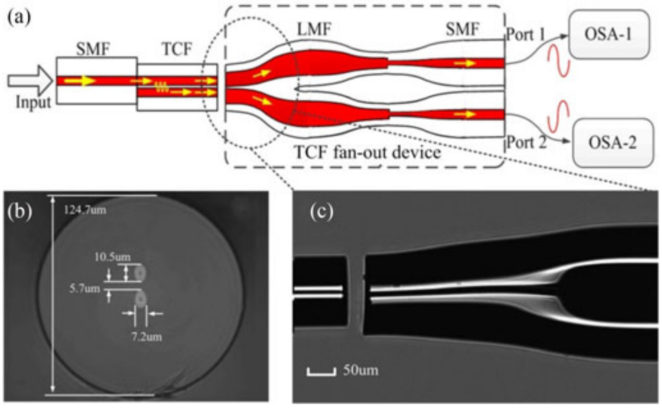

Fig. 4. (a) A schematic diagram of the proposed all-fiber TCF fan-out device used for accessing optical signals from the two cores of a matched TCF; (b) A cross-sectional microscopy image of the matched TCF; (c) A side-view microscopy image of the alignment between the TCF fan-out device and the matched TCF.

of 18 mA was employed in a splicing mode optimized for fibers with a diameter of 450 μm. Consequently, the contacted LMFs in the heated region were fused together due to surface tension in the melted silica. Arc discharge continued until the shape of the segment remained unchanged. The LMF bundle was then tapered by moving the two fiber holders and applying a continuous arc discharge at a relatively large current of 21 mA. The tapering process was repeated until the diameter in the center of the LMF-bundle taper was equivalent to the TCF cladding diameter. In addition, it should be noted that the imaging system was adjusted to capture a broader field of view in this step. This process is shown in Fig. 4(a4) and (b4).

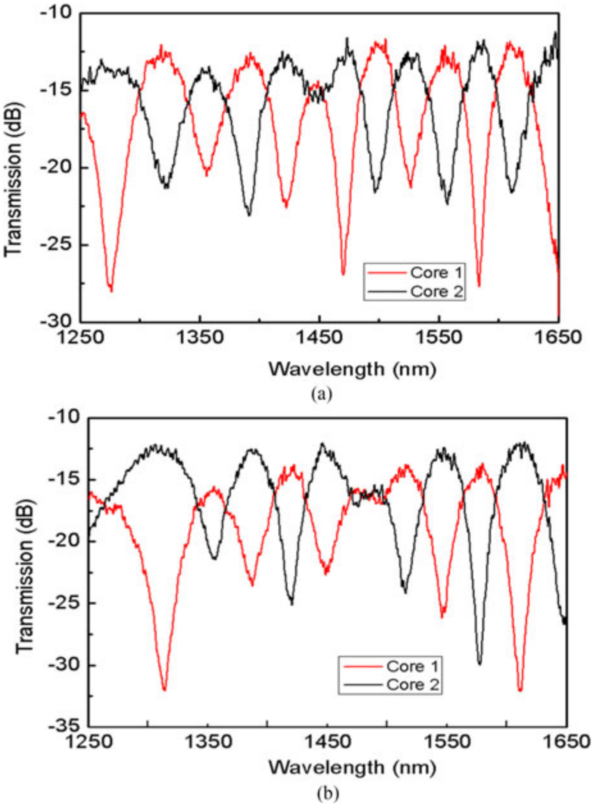

Fig. 5. Transmission spectra acquired from core 1 (red) and core 2 (black) in the matched TCF with different TCF lengths (L_0) of 150 mm (a) and 100 mm (b), respectively.

In step 5, the bi-tapered LMF bundle was removed from the fusion splicer and cleaved in the center of the LMF- bundle taper using a common fiber cleaver. This final step in the proposed all-fiber TCF fan-out device fabrication process is shown in Fig. 5(a5) and (b5). Fig. 3(b) shows a cross-sectional microscopy image of the cleaved end of the bi-tapered LMF bundle, which contains two semicircular cores with a cladding gap of approximately 4.5 μm. Fig. 3(c) and (d) show cross-sectional microscopy images of the bi-tapered fiber bundle as the broadband light was transmitted through the upper and lower LMF branches of the TCF fan-out device, respectively. Light could only be seen in the leading LMF branch, while no significant signal could be detected in the other LMF branch. This result indicates the two cores in the bi-tapered section of the TCF fan-out device were separated with very low crosstalk.

Moreover, it should be noted that the arc discharging, splicing, and tapering process described above were all automatically conducted by a computer program, which was executed in the microcontroller embedded in the fusion splicer. Hence, the device fabrication parameters could be precisely determined and it is beneficial for improving the repeatability and controllability of this fabrication method.

III. DEVICE CHARACTERIZATION AND DISCUSSION

We investigated the transmission characteristics for the proposed all-fiber TCF fan-out device, as shown in Figs. 4–7. The TCF fan-out device was spliced with two different TCF types

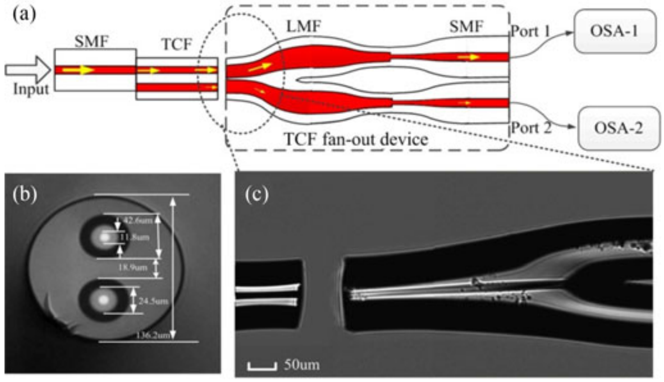

Fig. 6. (a) A schematic diagram of the proposed all-fiber TCF fan-out device used for accessing optical signals from the two cores of a mismatched TCF; (b) A cross-sectional microscopy image of the mismatched TCF; (c) A side-view microscopy image of the alignment between the TCF fan-out device and the mismatched TCF.

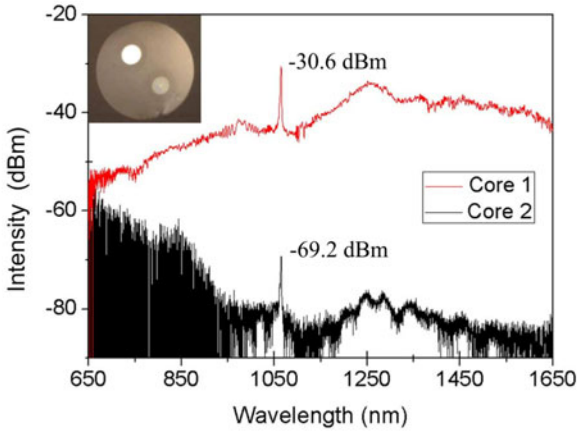

Fig. 7. Transmission spectra acquired from core 1 (red) and core 2 (black) in the mismatched TCF. (Inset: microscopy image of the mismatched TCF cross-section in which light was incident on a single TCF core.)

(i.e., the matched and mismatched TCFs). Cross-sectional microscopy images of these TCFs are shown in Figs. 4(b) and 6(b), respectively. It is evident the matched TCF features a small inter-core distance, whereas the mismatched TCF has a much larger inter-core distance.

We tested the proposed TCF fan-out device by accessing the optical signals from the cores of a matched TCF, as shown in Fig. 4. The matched TCF inter-core distance was ~5.7 μm, and strong coupling occurred between the two cores as predicted by coupled mode theory [26], [27]. The output power of core 1 and core 2 with a TCF length of L_0 can be expressed as

$$\begin{cases} P_1 = \frac{K^2}{\delta^2+K^2}\sin^2(\sqrt{\delta^2+K^2}L_0) \\ P_2 = 1 - \frac{K^2}{\delta^2+K^2}\sin^2(\sqrt{\delta^2+K^2}L_0), \end{cases} \tag{1}$$

where K is the coupling coefficient between the core modes of core 1 and core 2, and δ is the difference in the propagation constants of the two core modes. It is evident from (1) that the transmission power of each matched- TCF core varies periodically with the wavelength. The free spectral range (FSR) in the transmission spectrum of each TCF core is defined as [28]

$$\mathrm{FSR} = \frac{\pi/2}{(\delta K/\delta\lambda)L_0}, \tag{2}$$

which indicates that *FSR* is inversely proportional to both TCF length L_0 and the derivative of the coupling coefficient K with respect to wavelength. In other words, the FSR of the matched TCF transmission spectrum will decrease with an increasing TCF length [29].

In our experimental setup, as shown in Fig. 4(a), a broadband light source (BBS) with a spectral range of 1250–1650 nm was incident on one core of the matched- TCF via a lead-in SMF. Light was coupled between the two TCF cores, due to the coupling effect, and then separated at the output of the TCF via the proposed TCF fan-out device. An optical spectrum analyzer (OSA) (ANDO AQ6317B) was used to measure the optical signals separated from core 1 and core 2 in the TCF, respectively. Fig. 5(a) shows the transmission spectra acquired from the two cores of the matched TCF with a length of $L_0 = 150$ mm. These spectra show complementary sinusoidal waves, which are expected from (1). Moreover, Fig. 5(b) shows the transmission spectra acquired from the two TCF cores in case $L_0 = 100$ mm, which indicates FSR increases with a decreasing TCF length. This effect is in agreement with (2).

Furthermore, the connection loss of the proposed TCF fan-out device for the matched TCF could be deduced from Fig. 5, in which the total insertion loss of the structure (i.e., from the input port of SMF to the OSA) was ~12.0 dB. The connection loss of the SMF to TCF was measured to be ~2.0 dB in advance. Since the TCF was quite short ($L_0 = 100$ or 150 mm) in the experiment, the transmission loss of the TCF could be ignored. As a result, the connection loss of the TCF fan-out device for the matched TCF should be ~10.0 dB in total. In addition, it should be noted that the matched TCF had a core diameter of ~10 μm, whereas the LMF had a core diameter of ~105 μm. The insertion loss induced by the mode-field mismatch between the TCF and LMF was measured to be ~4.0 dB. As such, the insertion loss of the TCF fan-out device itself should be ~6.0 dB.

Efforts have been paid to reduce the connection loss of the TCF fan-out device. First, an LMF with a high NA of 0.22 was adopted, allowing more light to be constrained within the fiber core. And then, the fiber taper in the LMF- SMF spliced joint was created and optimized, reducing the transmission loss induced by the mismatch of the mode fields in the LMF and SMF [21]. Finally, the short fiber length and smooth shape of the bi-tapered LMF bundle ensured that propagation loss could be controlled at an acceptable level. Additionally, the short fiber length of the bi-tapered LMF bundle is also beneficial for an ultra- compact TCF fan-out device structure (~600 μm). It should also be noted that the connection loss of the proposed TCF fan-out device might further be reduced if a specially- designed LMF was employed with a more appropriate core diameter.

Moreover, it should be noted that the proposed TCF fan- out device was designed for silica TCFs. In case the all- silica TCF fan-out device is used for TCFs made by non- silica materials, such as polymer TCFs [30], the connection loss may further increase due to the high index-mismatch.

We tested the proposed TCF fan-out device used for accessing the optical signals from the two cores of a mismatched TCF, as shown in Fig. 6. The mismatched TCF featured two cores with a diameter of 11.8 μm. Each core was surrounded by a lower-index ring layer, which prevented the optical coupling between the two fiber cores. In the experimental setup shown in Fig. 6(a), another BBS with a wavelength range of 650–1650 nm was incident on one core of the TCF. The light separated from core 1 and core 2 by the TCF fan-out device was then analyzed using an OSA.

Fig. 7 shows the transmission spectra acquired from the two cores of the mismatched TCF. The inset includes a cross-sectional microscopy image of the mismatched TCF with light incident on a single TCF core. Both transmission spectra in the two cores exhibit pump peaks at 1060 nm, which were originally generated in the BBS light source. The intensities of these pump peaks were -30.6 and -69.2 dBm, respectively. This indicates that the proposed TCF fan-out device has successfully separated the optical signals from the two mismatched TCF cores with a low crosstalk of -38.6 dB.

IV. CONCLUSION

We have proposed and demonstrated a universal all-fiber TCF fan-out device via bi-tapering an LMF bundle, which consisted of two parallel LMFs tapered-spliced with two SMFs. A commercial fiber fusion splicer was used in the fabrication process for tapering and splicing. Experiments were conducted to test the proposed TCF fan-out device by connecting two different types of TCFs, i.e., the matched TCF with a small inter-core distance and the mismatched TCF with a large inter-core distance. Accessing optical signals from the two TCF cores has been demonstrated for both matched and mismatched TCFs, with a low crosstalk of about -38.6 dB and a connection loss of around 10.0 dB. In addition, the connection loss of the proposed TCF fan-out device could be reduced further using a specially-designed LMF with an optimized core diameter. As a result, the proposed universal all-fiber TCF fan-out device could have promising applications for novel TCF sensors and advanced SDM transmission systems.

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