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Invited Papers

Fusion splice techniques for multicore fibers

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ABSTRACT

Fusion splice techniques for multicore fibers (MCFs) are discussed here. We demonstrate a swing electrode system for uniform discharge and an end-view function for automatic and precise core alignment. The influence of the cleaved angle was investigated for stable and low-loss fusion splicing. Using these techniques, we achieved a low-loss splicing of not greater than 0.3 dB at all cores for a 32-core fiber and for all modes for a 2-LP-mode 12-core fiber, in which a precise core alignment and a uniform discharge of wide range were required. These results indicate that the techniques we proposed are promising for fusion splicing of MCFs.

1. Introduction

The capacity of conventional optical communication systems using single-mode fibers (SMFs) has been enlarged in accordance with the increase of communication traffic. However, it is indicated that the increase of the capacity is restricted to about 100 Tbit/s per fiber by a fiber fuse, near the Shannon limit [1]. Space division multiplexing (SDM) [2] is expected to become the key technology that overcomes the capacity limit of conventional systems. Multicore fibers (MCFs), which have several cores in one cladding, have been researched extensively as good candidates for SDM-transmission media. Some SDM transmission experiments over 1 Pbit/s per fiber have been demonstrated in 2012 [3,4], and recent experiments have achieved a capacity over 2 Pbit/s per fiber using single-mode MCFs (SM-MCFs) [5] or few-mode MCFs (FM-MCFs) [6]. In terms of spatial channel count (*SCC*) [7], which is expressed as the product of the mode count of each core and the core count, SM-MCFs with an *SCC* of over 30 have been reported [8–10], and some *SCCs* have reached over 100 by using FM-MCFs with large cladding diameters [11–13].

For the realization of long-haul SDM transmission with MCFs, fusion splicing between MCFs is one of the most indispensable techniques. A good splicing technique requires low losses at all cores and should be easy to implement. In this paper, we will discuss some techniques to achieve a good splicing. Firstly, a swing electrode system for uniform splice losses is demonstrated. Secondly, we propose an end-view function for a precise and automatic core alignment along the rotational direction. Finally, the influence of the cleaved angle for fusion splicing of MCFs is investigated.

2. Issues of fusion splicing for multicore fibers

MCFs have large cladding diameters and many outer cores except the center of the cladding, and these features cause several issues that do not exist for fusion splicing of conventional SMFs. In this section, we will explain three issues of fusion splicing for MCFs.

2.1. Uniform discharge for all cores

Fig. 1 shows the discharged condition of an MCF by a conventional static electrode system (StES). To achieve low and uniform losses at all cores of the MCF, a uniform discharge for all cores is necessary. However, it is difficult to discharge all cores uniformly by a StES because an MCF has many outer cores in a large cladding cross section, as shown in Fig. 1.

2.2. Core alignment for rotational direction

Fig. 2 shows the difference of alignment between SMFs and MCFs. For SMFs, alignment is needed only along the X and Y directions, as shown in Fig. 2(a). In the case of MCFs, alignment along the rotational direction (θ direction) is also necessary, in addition to the X and Y directions, as shown in Fig. 2(b). For the θ direction alignment, some methods have been proposed in previous literatures [14–17]. However, these methods have different limitations:

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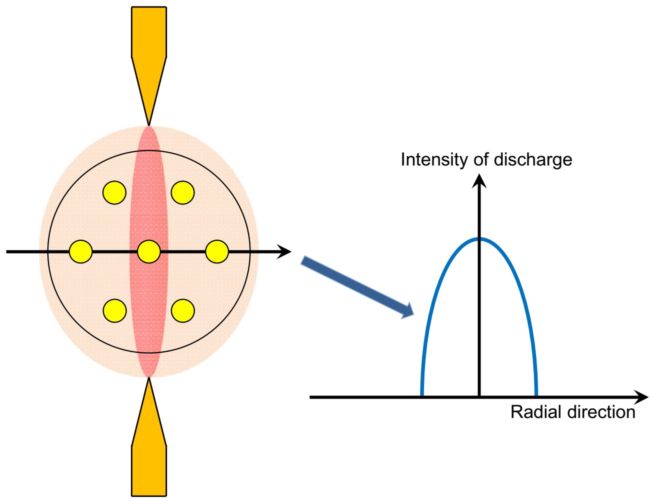

Fig. 1. Discharge by a conventional static electrode system.

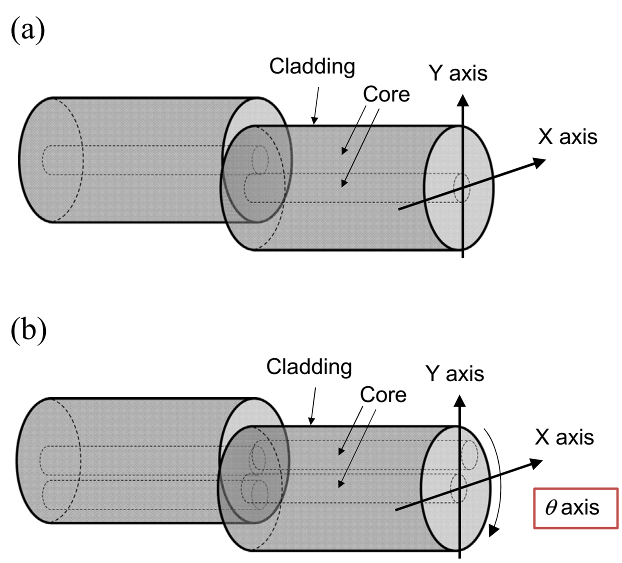

Fig. 2. Direction of core alignment for (a) single-mode fibers (SMFs) and (b) multicore fibers (MCFs).

one is not automatic; another is not passive; and the rest have difficulty in detecting a marker that is used for the identification of cores.

2.3. Influence by cleaved angle

Fig. 3 shows an image of the influence by the cleaved angle α for fusion splicing of MCFs. In the case of MCFs, the influence of the cleaved angle for the splicing condition is stronger than in the case of SMFs, because many outer cores exist in MCFs [15]. If the angle is too large, the outer cores become thinner or thicker after fusion splicing, as shown in Fig. 3. Therefore, it is necessary to find a range of cleaved angles for a low-loss fusion splicing between MCFs.

3. Swing electrode system for uniform discharge

Uniform wide area discharge is needed to discharge all cores uniformly. Some techniques such as discharge by three electrodes which are located in an equilateral triangle [15] and discharge by swing electrode system (SwES) [18] are proposed for wide area

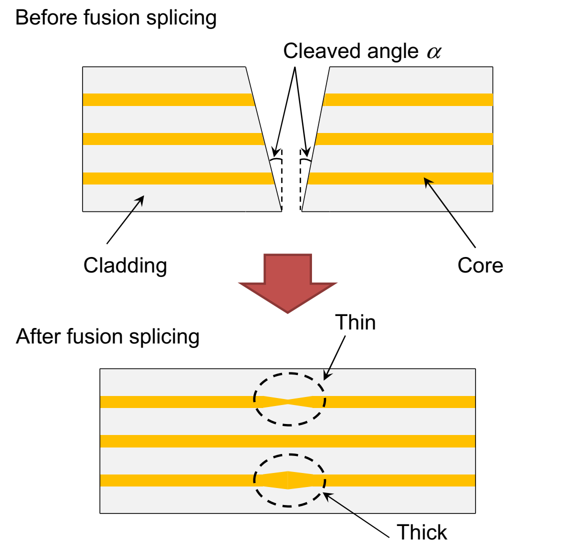

Fig. 3. Influence by cleaved angle for fusion splicing of multicore fibers (MCFs).

discharge. In this paper, we demonstrate SwES from among these techniques for uniform discharge of all cores in MCF. Fig. 4 shows a comparison of the discharged conditions between SwES and StES. The SwES, in which electrodes swing in the radial direction of fibers, realizes an extensively uniform discharge of all cores. Therefore, it is expected to equalize the fusion splice losses among all cores.

To confirm the effect of the SwES, we compared the splice losses using SwES with those using StES for a seven-core fiber shown in Fig. 5 [19]. The MCF has seven trench-assisted cores and a large mode-field diameter (MFD) of 12.1 µm on average at a wavelength of 1550 nm. The cladding diameter (*CD*) and average core pitch (Λ) of the fiber are 181 µm and 43.0 µm, respectively.

Fig. 6 shows an example of the distribution of measured fusion splice losses at 1550 nm at the outer cores by using SwES and StES. These losses were measured by unidirectional OTDR. The unidirectional OTDR measurements yielded accurate fusion splice losses because the same MCFs were used for this experiment. In Fig. 6, it is confirmed that the fusion splice losses by SwES are much more uniform than those by StES. This result indicates that SwES is capable of uniformly discharging each core in the MCF. Fig. 7 shows the histograms of fusion splice losses at 1550 nm by SwES and StES

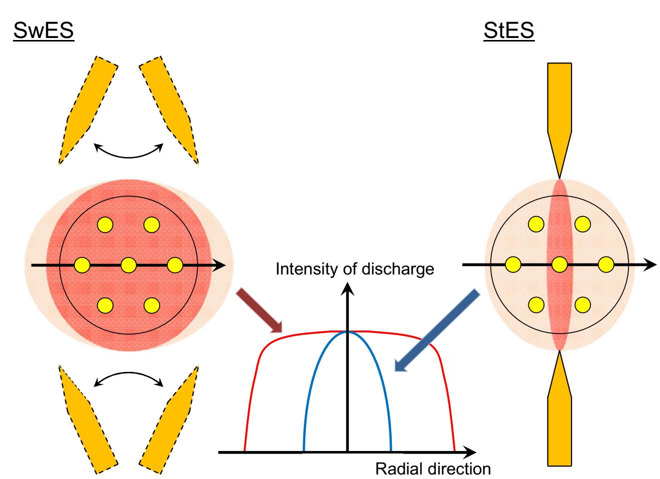

Fig. 4. Comparison of discharge by a swing electrode system (SwES) and a static electrode system (StES).

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