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Simultaneous Multi-Core Fiber-to-Fiber Self-Coupling with Near-Infrared Light-Induced Self-Written Optical Waveguide

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ABSTRACT Multi-core fibers (MCF) and multichannel optical waveguides have garnered significant attention as viable technologies for enhancing transmission capacity. However, the assembly of multichannel optical components encounters certain challenges, particularly in terms of alignment and takt time. To address these issues, this study proposed and demonstrated an optical coupling method using near-infrared (NIR) light-induced self-written (LISW) optical waveguide technology to simultaneously connect 4-core MCFs. All-solid LISW optical self-coupling between 4-core MCFs was achieved by employing an advanced selective polymerization process using light at 1310 nm wavelength. The resin used was characterized by the presence of an NIR dye in the monomer. The LISW optical waveguide core formation time was approximately 10 s, and the simultaneous 4-core formation was achieved within a short time. The average insertion loss (IL) of the all-solid LISW optical waveguide was 0.2 dB, and both the average IL of each channel and IL variation per channel were reduced compared with those of the butt joint. Thus, the LISW optical self-coupling compensated for the misalignment that occurred in the butt joint. Therefore, the LISW optical waveguide can also be used for the simultaneous optical self-coupling of multiple channels and is an effective method for reducing the fabrication time.

INDEX TERMS Optical coupling, Optical crosstalk, Optical fibers, Optical waveguides, Polymers, Resins, Self-assembly.

I. INTRODUCTION

The development of information and communication technology and social networking services and the expansion of video distribution services have resulted in a rapid increase in communication traffic. The global data volume is estimated to grow from 2 ZB in 2010 to 175 ZB in 2025 [1], and it will continue to explode thereafter [2]. Owing to ever-increasing communication traffic, current information and communication systems are predicted to reach their limits in terms of both transmission and processing capacities in the future. High-density optical transmission is required to increase transmission capacity. Consequently, transmission lines using multi-core fibers (MCFs) and multi-channel optical waveguides are used. Because multiple optical waveguides are configured for the outer diameter of conventional transmission lines, the transmission volume is expected to increase [3, 4]. However, the assembly of multichannel optical components is challenging and requires a long takt time owing to the increased number of optical connection points and the low-loss alignment required to achieve high-quality optical communication. Compared to that between conventional single-mode fibers, optical coupling between MCFs necessitates alignment along the direction of the rotational and conventional optical axes, which has been a bottleneck in the development of MCF connection technology. In an optical connection technique requiring active alignment, the takt time increases with the number of channels. Therefore, it is desirable to simultaneously connect multiple channels with a passive alignment in multichannel optical coupling.

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This study proposed and demonstrated an optical coupling between 4-core MCFs using the light-induced self-written (LISW) optical waveguide technology for simultaneous self-coupling of multi-channel optical waveguides. Simultaneous all-solid 4-core LISW optical self-coupling was successfully realized using near-infrared (NIR) light (1310 nm). Moreover, a low insertion loss of approximately 0.2 dB and low crosstalk of approximately -60 dB were achieved.

II. LISW OPTICAL WAVEGUIDE CORE

LISW optical waveguides interconnect optical components using a photocured-resin-based optical waveguide. Specifically, when light is emitted from an optical fiber into a photocurable resin, the resin hardens along the direction of beam propagation to form an optical waveguide. LISW optical self-coupling between optical fibers was performed using the process shown in Fig. 1. (1) Opposing optical fibers are placed in a photocurable resin and irradiated with light to cure the resin from both optical fibers. (2) The irradiated light causes the resin to cure, starting from the tip of the optical fiber core. (3) The cured resin is interconnected at the point where the light emitted from the opposing optical fibers overlaps. (4) Upon stopping light irradiation, the polymerization reaction is completed, and the LISW optical waveguide core is obtained [5–24]. The key features of the LISW optical waveguide core formation process are described in steps (2) and (3). Waveguide growth starts at the end face of the optical fiber, and the grown core is interconnected at the point where the beams emitted by the two ways overlap; the LISW optical waveguide core is interconnected at the point of highest light intensity in the overlapping beams, thereby facilitating interconnection even if in case of misalignment of opposing optical fibers. Consequently, the alignment between opposing optical fibers can be alleviated, and LISW optical self-coupling can be performed in batches regardless of the number of cores, provided the appropriate output light can be emitted from the optical fiber. In addition, the LISW optical waveguide is expected to reduce the insertion loss (IL) due to the shape of the waveguide end face. When the end face of the waveguide is treated using methods other than polishing, losses due to the end face shape may occur, particularly in butt joints. Moreover, this may result in return losses. The LISW optical waveguide enables improving these loss parameters, suggesting the potential for relaxing the end-face condition accuracy. Therefore, direct optical coupling to optical fibers is feasible for silicon and polymer optical waveguides, which are difficult to connect via connectorization or fusion splicing.

LISW optical waveguide cores can be fabricated using ultraviolet (UV)-blue light [5–14], which is the curing wavelength of common photocurable resins. More recently, NIR-LISW optical waveguides were realized in the 1070–1550 nm band [22–24]. The appropriate selection of the wavelength to form the LISW optical waveguide is important for achieving the desired composition and polymerization conditions of the photocurable resin.

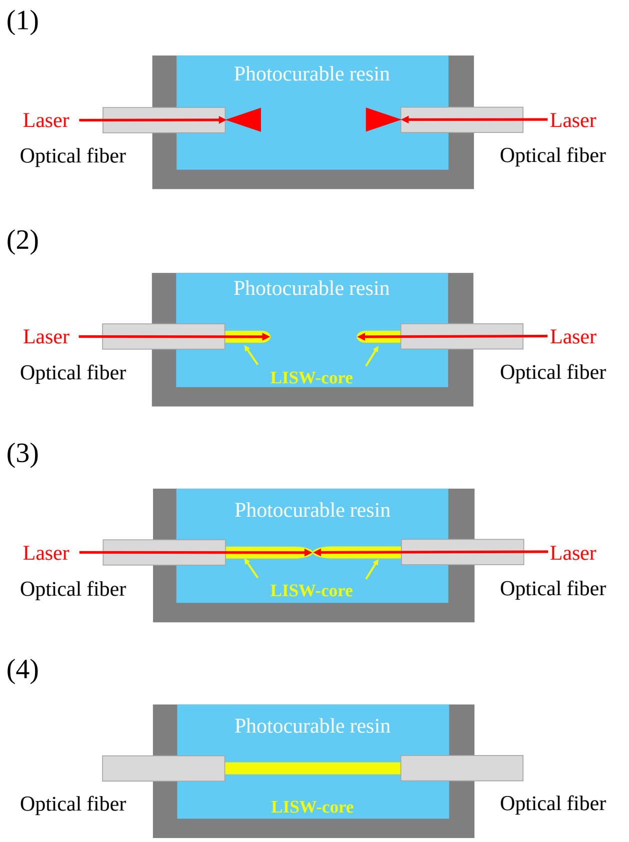

FIGURE 1. Process steps for LISW optical core.

In this study, NIR light (1310 nm) was chosen as the wavelength for core formation, considering the amount of optical attenuation in the optical fiber. UV-blue light is widely used for polymerization; however, it is accompanied by large optical attenuation in the optical fiber. In the case of a long optical fiber, securing a sufficient optical output is challenging, which renders LISW optical self-coupling difficult. However, NIR light has low optical attenuation, rendering the interconnection of long optical fibers feasible. Compared to 1550 nm light, 1310 nm light experiences attenuation within the optical fiber; however, it provides sufficient optical power to ensure resin curing, and its higher photon energy makes it suitable for curing the resin. Moreover, it offers the advantages of applicability to automatic optical coupling with NIR telecommunication light sources and enables achieving single-mode beam quality using single-mode fibers.

III. LISW OPTICAL WAVEGUIDE CLADDING

The cladding was fabricated using an advanced selective polymerization process [24]. This method used a mixed resin to form the core and cladding with different refractive indices. In this advanced selective polymerization process, resins containing monomers with two different types of reactive functional groups were prepared. The materials exhibited different chemical reaction rates and refractive indices. For core formation, one of the two monomers was selectively polymerized via irradiation with 1310 nm light. Immediately after core formation, a concentration difference was induced between two monomers. This concentration difference was alleviated via interdiffusion between the monomers at the boundary of the core and cladding. This interdiffusion generated a refractive-index difference between the core and cladding. By photocuring the uncured resin through fiber propagation of short-wavelength light, the interdiffusion was stopped, and an all-solid LISW optical waveguide was obtained. Following the formation of the LISW optical waveguide core with NIR 1310 nm light, the cladding was solidified by propagating 405 nm wavelength light from both fibers after approximately 2 min of interdiffusion.

IV. EXPERIMENTAL

Photopolymerization via NIR light was achieved via the addition of an NIR-absorbing dye and the corresponding photoinitiator to the resin mixture [18–21, 23]. The composition of the NIR-photocurable resin is shown in Fig. 2. Dipentaerythritol hexaacrylate (Fig. 2a), 9,9-Bis [4- (2-acryloyloxyethyloxy) phenyl] fluoren (Fig. 2b), and tricyclo decanedimethanol diacrylate (Fig. 2c)—which exhibit photoradical polymerization − and 4,4'-Bis [(3-ethyl-3-oxetanyl) methoxymethyl] biphenyl (Fig. 2d) and EG-200 (Fig. 2e)—which exhibit photocationic polymerization−were used as monomers for the photopolymerization. When these monomers were applied to the advanced selective polymerization process, the primary component of the core was an acrylic monomer, because photoradical polymerization exhibits a faster reaction rate than photocationic polymerization. The amounts of the acrylic and glycidyl ether monomers were determined by considering the refractive indices of the monomers. NIR-absorbing dye named CIR-960 (Fig. 2f) was used as NIR sensitizer. Tetrabutylammonium butyltriphenylborate (Fig. 2g) was used as photoradical polymerization initiator. Diphenyl [4- (phenylthio) phenyl] sulfonium trifluorotris (pentafluoroethyl) phosphate (Fig. 2h) was used as photocationic polymerization initiator. In addition, 9,10-dibutoxyanthracene (Fig. 2i) was added as a UV sensitizer for cladding formation with light propagating at 405 nm. This is because the two photoinitiators do not exhibit absorption in the 405 nm wavelength band.

A schematic of the LISW optical waveguide fabrication system is shown in Fig. 3. The 4-core MCF used in the experiment had a mode field diameter of 7.4–8.5 µm at 1550 nm, cladding diameter of 124 ± 1 µm, NA of 0.14–0.17, core pitch of 50 µm, and cutoff wavelength of 1300–1500 nm. Fig. 4 shows an end view of the 4-core MCF.

Two MCFs were prepared and placed opposite to each other on a V-groove substrate with a 100 µm space between them. This space was filled with a photocurable resin mixture. A laser diode (LD) with a wavelength of 1310 nm was used as the light source for LISW optical waveguide core formation.

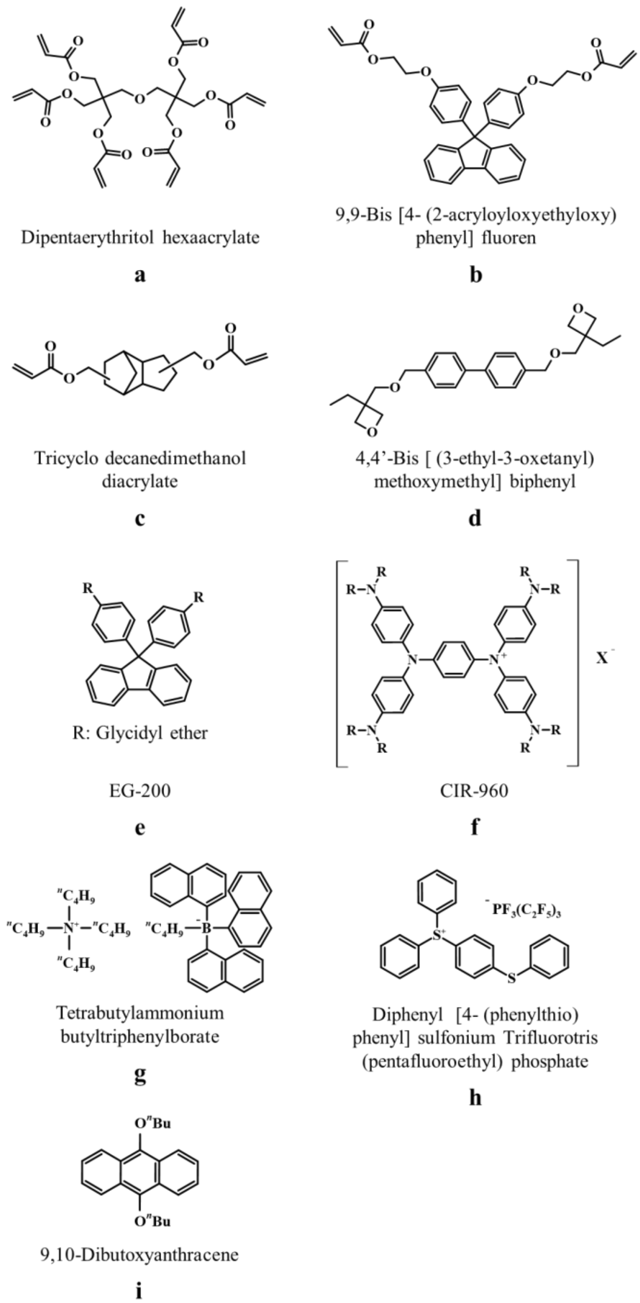

FIGURE 2. Composition of NIR-LISW resin.

The 1310 nm light was simultaneously irradiated for 10 s at 400 µW for each channel through a 1 × 4 optical coupler, and the interdiffusion of resin was performed for 2 min. Subsequently, the 1 × 4 optical coupler was removed, and 405 nm LD light was irradiated through the MCF for 20 s at 1 µW output power from both sides of the MCF to form the cladding.

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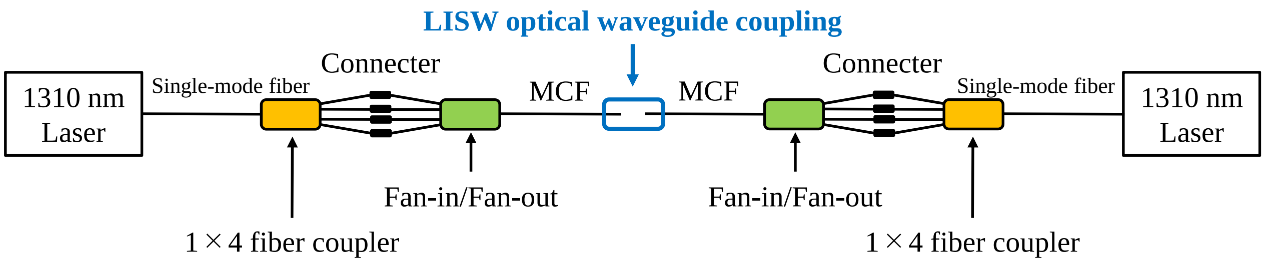

FIGURE 3. Experimental diagram of NIR-LISW core between 4-core MCFs.

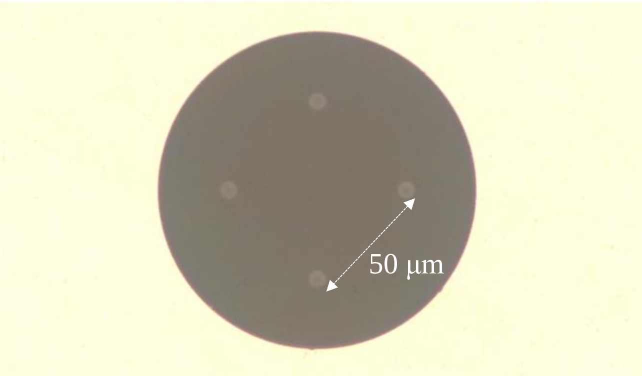

FIGURE 4. End face image of 4-core MCF.

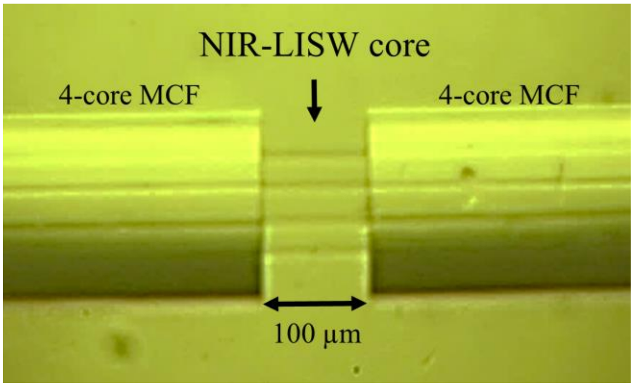

FIGURE 5. NIR-LISW core between 4-core MCFs.

A distributed-feedback LD light source with a wavelength of 1550 nm was connected to each channel of the 4-core MCF. The IL of each channel was measured as a reference. Thereafter, the MCF was cut, and the end faces were treated with a cleave cut. The MCFs were placed opposite to a glass V-groove substrate with a slit in the center, and passive alignment was performed on the horizontal and vertical axes of the MCF. After bringing the opposing MCFs closer using a micrometer, active alignment was performed along the rotational axis direction. The IL of each channel was measured as that of a butt joint. The IL of each channel was subsequently measured after all-solid LISW optical waveguide formation with a 100 μm gap between the MCFs. Further, crosstalk measurements were performed by switching the receiving channel with respect to the projection side.

After conducting crosstalk measurements, the formed NIR-LISW was immersed in an organic solvent to detach it from the 4-core MCFs. Resin mixture was filled into the space of the V-groove substrate, and the fabrication of the NIR-LISW optical self-coupling was performed again. To evaluate the reproducibility, this fabrication process was repeated 10 times, measuring the IL each time.

V. RESULTS

Irradiation of 1310 nm light from each channel of the MCF facilitated the polymerization of the NIR photocurable resin. Consequently, simultaneous formation of an LISW optical waveguide core in each channel of the MCF was realized. A microscopy image of the simultaneous 4-core LISW optical waveguide growth is provided in the Supplementary Material, Movie S1. Bidirectional irradiation of 1310 nm light resulted in MCF-to-MCF self-coupling. A microscopy image of self-coupled 4-core MCFs is shown in Fig. 5 and Movie S2. The IL of the channel-by-channel butt-jointing of MCFs and that of all-solid LISW optical waveguide employing the advanced selective polymerization method are shown in Fig. 6. In the case of butt-jointing between MCFs, the average IL was 0.8 dB. Upon LISW optical self-coupling, the average IL was 0.2 dB. Further, when butt-jointed, the maximum and minimum losses were 1.0 and 0.6 dB, respectively, indicating a difference of 0.4 dB. However, the maximum and minimum losses after LISW optical self-coupling were 0.3 and 0.2 dB, respectively, with a difference of 0.1 dB. The measurement results of the crosstalk are presented in Table 1. The crosstalk obtained via measurement ranged between -57.1 and -65.8 dB.

The results of repeated coupling of LISW optical waveguides using the same MCFs are shown in Fig. 7. After conducting 10 couplings, there were a total of 40 measurement channels. Among these, 6 channels showed 0.2 dB IL, 9 showed 0.3 dB IL, 16 showed 0.4 dB IL, 8 showed 0.5 dB IL, and 1 showed 0.6 dB IL. Calculating the relative frequencies revealed that 97 % of all couplings were achievable with IL of 0.5 dB or less.

VI. DISCUSSIONS

LISW optical self-coupling between MCFs using 1310 nm wavelength light was achieved by fabricating a photocurable resin containing an NIR dye. The obtained cores exhibited a

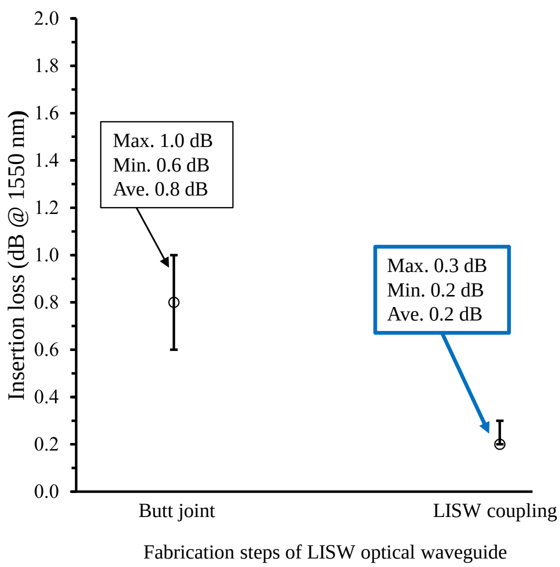

FIGURE 6. **Insertion loss of butt joint and LISW coupling by between 4-core MCFs.**

TABLE I

Cross talk of coupling by between 4-core MCFs (dB @ 1550 nm)

Ch. No.	1	2	3	4
1	-	-57.5	-64.2	-62.1
2	-58.2	-	-61.2	-62.8
3	-56.4	-57.1	-	-65.8
4	-57.2	-64.8	-65.6	-

straight shape, and the simultaneous formation of the LISW optical waveguide was achieved without coupling with another channel. Although the 1310 nm wavelength light irradiated from the MCF diffracted into the resin in the initial stage of the LISW optical waveguide core formation, the resin cured from the end face of the MCF core, where the light intensity was highest. The 1310 nm light emitted from the end face of the cured resin formed a straight LISW optical waveguide core without diffusion owing to the self-focusing effect. Consequently, it could be properly connected to the target channel without coupling to another channel.

An air gap of 100 μm was provided between the two MCFs, and the IL of each channel was measured. The average, maximum, and minimum IL values were 5.8, 6.2, and 5.6 dB, respectively. The IL was drastically reduced by optically interconnecting the two MCFs. Butt-jointing was realized between the two MCFs, and the average IL was 0.8 dB. This IL is attributed to various factors such as misalignment, MCF end face geometry, and reflection losses. The average, maximum, and minimum ILs when the MCFs were butt-joined decreased after LISW optical self-coupling. This indicates that the LISW optical waveguides has successfully addressed the aforementioned factors, including misalignment.

Furthermore, LISW optical waveguides can couple multiple channels simultaneously. The waveguide core grew

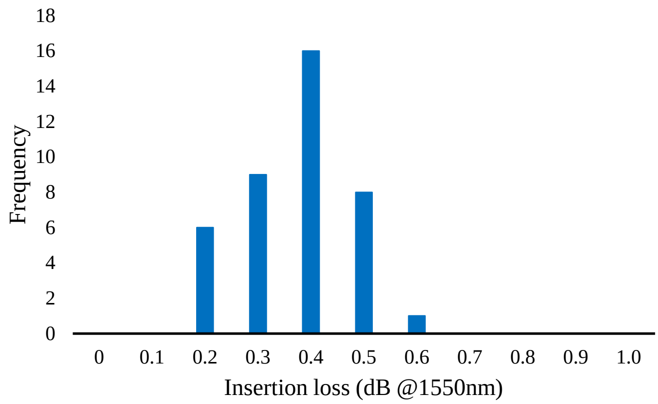

FIGURE 7. **Results of repeated LISW coupling.**

in only 10 s, and even with four cores, the time did not increase because of the simultaneous growth. The total takt time was 210 s, including approximately 120 s for interdiffusion and 20 s for cladding solidification. The total takt time can also be reduced to 150 s if a violet laser irradiates the LISW optical core simultaneously to solidify the cladding. The adaption of highly controlled LISW optical waveguide technology to multichannel optical self-coupling offers two advantages: (1) yield improvement by mitigating misalignment and shape of the waveguide end face; (2) fabrication time improvement by simultaneously connecting multiple channels.

As shown in Table 1, the crosstalk was sufficiently low and uniformly stable in each channel, lying at the same level as that before cutting the 4-core MCF used in the experiment. Moreover, no light leakage was observed between the channels of the self-coupled LISW optical waveguides.

The results of repeated couplings of the LISW optical waveguides showed that 97 % of the total connections were achieved with an IL of 0.5 dB or less. Therefore, this process has demonstrated reproducibility, and the obtained LISW optical waveguides clearly exhibit low losses.

VII. CONCLUSION

All-solid LISW optical self-coupling between 4-core MCFs was achieved using 1310 nm wavelength light. The resin was characterized by the presence of an NIR dye in the monomer. The LISW optical waveguide core formation time was approximately 10 s, and the simultaneous 4-core formation was achieved within a short time. The average IL of the all-solid LISW optical waveguide fabricated using the advanced selective polymerization process was 0.2 dB, and both the average IL of each channel and the IL variation per channel were reduced compared to that of the butt joint. Thus, the LISW optical self-coupling compensated for the misalignment that occurred in the butt joint. These results indicate that the LISW optical waveguide can also be used for the simultaneous optical self-coupling of multiple channels and is an effective method for reducing the fabrication time.

Application of LISW optical self-coupling between 7-core MCFs is currently underway.

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