Fusion splicing of double-clad specialty fiber using active alignment technology

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The fusion splicing of double-clad (DC) specialty fibers based on active alignment is crucial to the investigation of high-power monolithic fiber lasers. Given the wave-guiding characteristic of DC fiber, a light stripper is introduced in an active alignment experiment. We propose a novel method for stripping light that is convenient, highly efficient, and low cost. This method is also effective for low-numerical-aperture beams that escape from the fiber core. A splice loss as low as 0.05 dB is achieved.

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Double clad (DC) fibers overcome the difficulty of coupling pump light by increasing fiber diameter and support good beam quality by reducing the numerical aperture (NA)[1,2]. Taking advantage of the specialty design of DC fibers, monolithic fiber lasers with output powers approaching the kilowatt range have been reported[3−5] and are widely used in many fields, such as materials processing and military applications[6−8]. To replace the bulk-optic interface, fiber fusion splicing is employed to interconnect all-fiber components. In high-power fiber lasers, the lost optical power induced by the fusion splice joint leads to a decrease in laser efficiency and laser beam quality, and probably destroys all-fiber components and the pump source. Thus, fusion splicing plays an important role in the performance and reliability of high-power fiber lasers.

Generally, splicing hardware employs image-based alignment in which the microscopic view of the fiber core is used for alignment purposes. However, to improve pump absorption, a variety of non-circular shapes of DC fiber cladding have been developed, such as rectangular, D-shaped, octagonal, and flower-shaped. The eccentric cladding shapes of these DC fibers have become asymmetric because of manufacturing errors or their intrinsic features. The distinct cladding of DC fibers refracts light rays irregularly and prevents the fiber core from being imaged accurately. Due to the misalignment of the standard method, fusion splicing of DC fibers results in a loss of more than 0.1 dB.

Few reports exist regarding special fusion splicing techniques applied to DC fibers. For example, Li *et al.* reported a DC fiber etching technique for weakening core mismatches that achieves a splice loss of 0.05 dB[9]. However, this method does not improve the precision of alignment, and eroded DC fibers obviously have limited applications in fiber lasers. To precisely align the fiber tips and reduce splicing loss in DC fibers, active alignment technique that involves transmitting light power is used in our experiment. This method is crucial to the connection of DC fibers in high-power fiber lasers. A new stripper is developed for dissipating cladding light with low NA during active alignment. Using this novel method in the active alignment operation, the splice loss is reduced to 0.05 dB.

Instead of relying on images of the fiber tips, active alignment, a more effective strategy, was employed. The developed system consisted of a laser source, an optical power meter, and a conventional fiber fusion splicer. The experimental setup is shown in Fig. 1. As depicted in the inset of Fig. 1, the delivery fiber of the laser source and the first DC fiber were spliced together. An optical power of 230 mW at 1550 nm was launched into the core of the first DC fiber via the delivery fiber. The optical power meter was a Molectron EPM-2000, with a response time of 1 s and a resolution of 1 mW. The commercially available fusion splicer, manufactured by Vytran, used a heating filament with an inverted Ω shape.

In our experiment, two compatible DC fibers, manufactured by Nufern, were used for splicing. These had a core diameter of 20 μm (NA = 0.06), a cladding diameter of 400 μm (NA = 0.46), and a coat diameter of 550 μm (refractive index 1.38). The cladding shape of the first fiber was circular and that of the second fiber was octagonal, as shown in Fig. 2, which shows the cladding shape as observed by surface-mapping microscope. The laser source launched light into the first DC fiber while the power meter monitored the amount of optical power at the free end of the second DC fiber.

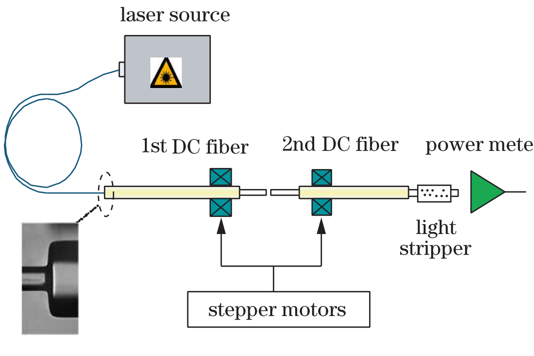

Fig. 1. Experimental arrangement of fusion splicing of DC fibers with active alignment technology.

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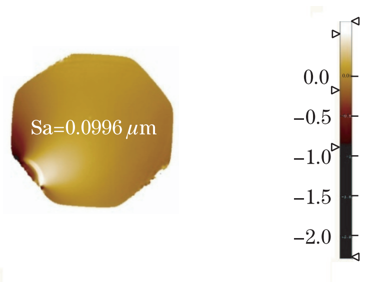

Fig. 2. Inner cladding shape of the second DC fiber measured by surface mapping microscope. Sa: surface roughness.

The two tips of the DC fibers were separated by a 3-μm air gap and laterally driven to the location that yielded the maximum transmitted power, which was assumed as the optimal fiber alignment.

Inevitably, part of the optical power in the core of the first DC fiber was coupled into the cladding of the second one because of the core offset during alignment. Unlike conventional optical fibers, DC fibers are manufactured with a polymer coating with a refractive index lower than that of the cladding, which deliberately traps optical energy in the cladding. In this special case, the light that was not coupled into the core of the second fiber could be guided into the cladding and detected by a power meter. Thus, the optical power measured at the end of the second DC fiber was constant and alignment could not be completed.

Stripping the cladding light induced by the core mismatch is important. One approach is to recoat the DC fiber with a high-index ultraviolet (UV) curable adhesive downstream of the splice joint[10]. The total internal reflection at the cladding interface is destroyed and light is no longer confined in the cladding. The magnitude of the stripping is a function of the difference in indices between the cladding and the recoat, as well as the NA of the light to be stripped. To predict the light attenuation at different NAs, the model of the optical energy distribution between the cladding and the recoat was established. The normalized stripped optical power was calculated as a function of the refractive index of the UV adhesive based on Fresnel formulas, which is shown in Fig. 3. It proved that effective attenuation of high-NA light could be obtained by recoating the fiber. However, for the light with a 0.06 NA, the attenuation of this type of stripper was extremely index-dependent. When the adhesive with a refraction index identical to that of the cladding was not available, the stripper only produced around 20% attenuation depending on calculation. This suggests that the low-NA cladding light that escapes from the core of the DC fiber is not stripped effectively within a reasonable distance. A large amount of light propagating in the second fiber cladding would cause a serious reduction in the sensitivity of the active alignment, especially when the output power of the laser source is relatively low.

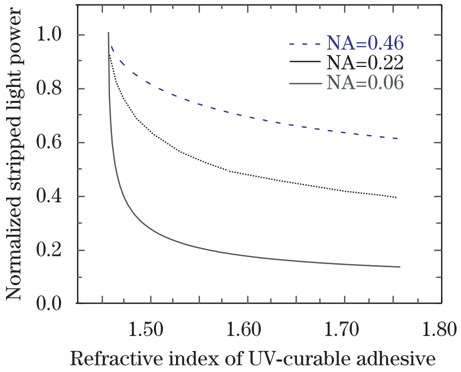

Fig. 3. Normalized stripped light power varies with the index of the UV-curable adhesive.

To increase the sensitivity and precision of the active alignment of the DC fibers, a novel light stripper was introduced and significant attenuation of the low-NA cladding light was achieved within a short length. At the free end of the second DC fiber, the coating was peeled from the fiber. Then, the fiber cladding was polished directly by sandpaper with a grit size of 8 μm. The fiber cladding was manually polished approximately two hundred times until the surface of the DC fiber cladding was sufficiently rough. A micrograph of the polished fiber is shown in Fig. 4. The surface of the fiber cladding completely lost its optical mirror reflection. Thus, unlike recoating the fiber, polishing the fiber utilizes optical scattering to enable the rapid stripping of the low-NA light. As soon as the light reached the polished area, the light rays were partially scattered out of the fiber cladding and the NA of other rays increased due to the rough surface. As light passed through this novel structure again, many unstripped rays with increased NA dissipated. By changing the optical characteristic of the cladding surface, more than 50% of the low-NA rays in the cladding of DC fiber were stripped along the entire 20-mm length and the light in the fiber core became uninterrupted.

The attenuation of the low-NA light was improved significantly by the new stripper at the end of the fiber chain. The relative position of the two DC fibers was adjusted in a radial direction. The relationship between the optical power measured by the detector and the deviation of fiber cores is shown in Fig. 5, which indicates that the sensitivity of alignment is very high. To define the horizontal axis in Fig. 5, the deviation of fiber cores was considered zero when the maximal output power was obtained during alignment. Furthermore, the stepper motors drove two DC fibers with a control resolution of 0.1 μm. Figure 6(a) illustrates the ideal situation where two fiber cores are aligned well by an active method. When this is the case, the lateral offset of the fiber cores could be observed in the microscopic image.

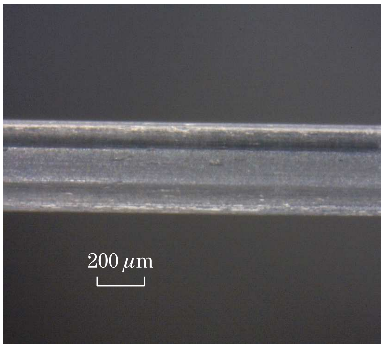

Fig. 4. Image of a polished 20/400-μm DC fiber employed as a light stripper.

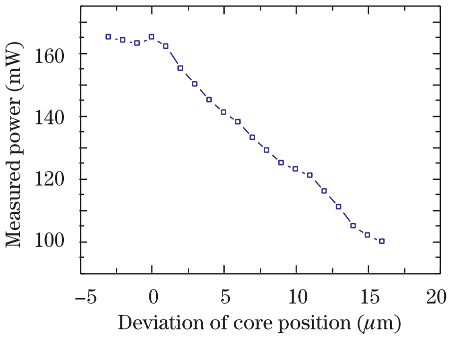

Fig. 5. Power measured by EPM-2000 varies with the deviation of the two fiber cores during active alignment.

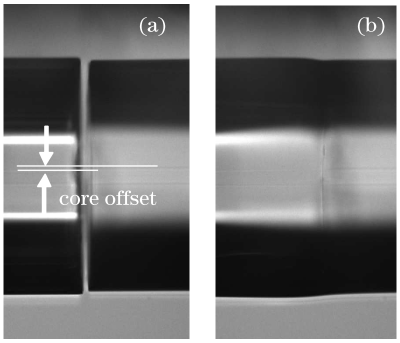

Fig. 6. (a) Result of the active alignment; in this case, the cores are matched well. (b) Image of fusion splicing of the 20/400-μm DC fibers with circle cladding and octagonal cladding, respectively.

This offset was caused by the irregular refraction of light in the eccentric cladding, which also confirmed our analysis. Then, two DC fibers were spliced using a Vytran splicing workstation. The microscope image of the fusion splice is shown in Fig. 6(b). After splicing, 227 mW of power was measured using a power meter; the optical loss induced by the splice joint was approximately 0.05 dB. The surface tension during the splicing process could cause fiber radial offset. Consequently, the splicing was implemented with a slight reduction in splicing power and an increase in splicing time to prevent mismatch of the fiber core.

In conclusion, we have demonstrated a low fusion splice loss of 0.05 dB for DC fibers using an active alignment configuration. To significantly improve the quality of the active alignment, a new method for stripping low-NA light rays from the fiber cladding is successfully accomplished. This novel stripper is inexpensive, fast, effective, and can remove residual pump light in fiber lasers with a master oscillator power amplifier (MOPA) structure. Fusion splicing of DC fibers with good optical coupling efficiency would ensure that high-power all-fiber lasers operate reliably.

References

1. E. Snitzer, H. Po, R. P. Tumminelli, and F. Hakimi, "Optical fiber lasers and amplifiers" US Patent 4,815,079 (Mar. 21, 1989).
2. V. P. Gapontsev, M. Vyatkin, and V. Grigoriev, "Large mode area fiber for low-loss transmission and amplification of single mode lasers" US Patent 7,283,714 (Oct. 16, 2007).
3. V. Gapontsev, D. Gapontsev, N. Platonov, O. Shkurikhin, V. Fomin, A. Mashkin, M. Abramov, and S. Ferin, in *Proceedings of 2005 IEEE Conference on Lasers and Electro-Optics Europe* 508 (2005).
4. P. Yan, S. Yin, and M. Gong, Chin. Opt. Lett. **6,** 580 (2008).
5. S. Yin, P. Yan, and M. Gong, Opt. Express **16,** 17864 (2008).
6. C. G. Carlson, P. D. Dragic, B. W. Graf, R. K. Price, J. J. Coleman, and G. R. Swenson, Proc. SPIE **6873,** 68730K (2008).
7. P. Zhou, Z. Liu, X. Xu, F. Xi, X. Chu, and H. Ma, Chinese J. Lasers (in Chinese) **36,** 1442 (2009).
8. L. Mei, G. Chen, X. Jin, M. Zhang, and M. Chen, Chinese J. Lasers (in Chinese) **37,** 2091 (2010).
9. Y. Li, S. D. Jackson, and S. Fleming, IEEE Photon. Technol. Lett. **16,** 2502 (2004).
10. A. Wetter, M. Faucher, and B. Sévigny, Proc. SPIE **6873,** 687327 (2008).