Multicore Fiber Manufacturing Technologies Using Modified Cylinder Method

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ABSTRACT It is expected that the increase in transmission capacity in optical communication systems using conventional Single-Mode Fibers (SMFs) will reach its limit, and that the early commercialization of Space-Division Multiplexing (SDM) transmission technology using Multicore Fibers (MCFs) is forecasted. In this report, we introduce the research and development trends of MCF manufacturing technology reported so far from the viewpoint of improving the manufacturability for the practical use of MCF. In addition, we report on a new method that we are developing as a new manufacturing method in order to solve the issues (drilling cost, limitation of preform size) in the drilling method, which is currently the most widely used manufacturing method. In principle, the modified cylinder method has the advantages of larger size and lower cost of the preform, and we have fabricated MCFs from the preform by optimizing the design of the modified cylinder method, and have achieved a low attenuation that is comparable to that of the MCF fabricated by the drilling method.

1. INTRODUCTION

In recent years, Internet traffic has increased rapidly in response to the development of video distribution services and various Web services. Facing the rapid increase in Internet traffic, optical communication systems are required to have larger transmission capacity. Various technological innovations have enabled the transmission capacity of optical communication systems to be increased. However, in recent years, it has been suggested that the increase in transmission capacity per fiber in optical communication systems using conventional SMFs has reached its limit due to the nonlinear phenomena, etc. occurring in the optical fiber. Therefore, in recent years, SDM transmission technology has been attracting attention as a technology to break through the limit of the increase of transmission capacity per fiber. Various research and development activities have been conducted on optical fibers for SDM transmission. Among them, the development of SDM transmission technology using MCF has attracted much attention, and many research cases have been reported. For example, a high-capacity transmission using 19-core fiber[1), 2)] has been reported. Furthermore, transmission experiments in which the number of SDM channels exceeds 100 have been reported by combining mode multiplexing technology in each core of the MCF, and transmission capacities exceeding 10 Pb/s per fiber have been achieved[3), 4)]. In the SDM transmission experiments using these MCFs, a significantly larger capacity was achieved compared to transmission systems using conventional SMFs, while the cladding diameter of MCFs was 200 μm or more, which is much larger than that of conventional SMFs (125 μm). When fibers with significantly larger cladding diameters are used in actual transmission systems, there are significant issues from the viewpoint of ensuring mechanical strength reliability due to bending, etc. In recent years, the use of MCFs in actual transmission systems has been accelerated. Recently, MCFs with a cladding diameter of 125 μm, which have good connection affinity with conventional SMFs, have been reported[5), 6)] with the goal of early application to actual transmission systems. The use of MCFs with standard cladding outer diameter is a great advantage because it allows the use of existing technology in terms of tools and techniques used for cutting and splicing fibers, fusion splicing technology, and cable construction.

In order to actually realize a transmission system using MCF, in addition to using MCF with a standard diameter, improvements in MCF manufacturing technology are required. In particular, cost reduction and mass production by increasing the size of the preform are necessary. In this report, we introduce research and development trends in MCF manufacturing technology from the viewpoint of improving manufacturability for the practical use of MCF. In addition, we report on the manufacturing technology of MCF using a modified cylinder method that is under development.

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2. VARIOUS MANUFACTURING TECHNOLOGIES FOR MCF PREFORM

This chapter describes the MCF manufacturing technologies that have been reported so far. They are in the process of being developed for practical use, and each method has its own characteristics. Table 1 shows the main MCF manufacturing methods under investigation.

2.1 Drilling Method

In the drilling method, a quartz rod is perforated with a drill to produce a clad rod with multiple holes, and a core rod containing a core is inserted into the holes of the clad rod to produce the MCF preform. The advantages of the drilling method include a high core positioning accuracy and a high degree of freedom in core placement. The issues are the high cost of drilling and the limited length of drilling. Currently, the drilling method is the most widely used method for manufacturing MCFs (Figure 1).

2.2 Stack and Draw Method

The stack and draw method[7] has been reported as a manufacturing method for MCF preform different from the drilling method. In the stack and draw method, core rods are inserted into a quartz pipe, and by appropriately designing the inner diameter of the pipe and the outer diameter of the core rods, the quartz pipe and the outer diameter of each core rod are constrained to place the core on the lattice points of the hexagonally-most-dense structure. The advantages of the stack and draw method are the ease of processing the components and the small constraints of the preform size. One issue is that the cores can only be placed on the lattice points of the hexagonally-most-dense structure. In addition, the positioning accuracy of the core depends on the clearance between the inner diameter of the pipe and the outer diameter of the core rod, but in the actual fabrication process, a clearance is required when the core rod is inserted into the pipe. Since this clearance leads to core misalignment, a poor core positioning accuracy becomes an issue. In addition to the MCF manufacturing process, the stack and draw method has been used in many other applications as a manufacturing process for hollow core fibers (Figure 2).

2.3 Over-cladding Bundled Rods Method

Recently, an over-cladding bundled rods method[8] has been proposed as a method for manufacturing MCF preforms. In the over-cladding bundled rods method, a silica

Table 1 MCF manufacturing technologies.

	advantages	issues
Drilling method	- High core positioning accuracy - Arbitrary core placement	- Drilling cost - Restriction of drilling length
Stack and draw method	- Easy assembly - Smaller size restrictions	- Core Positioning Constraints - Low core positioning accuracy
Over-cladding bundled rods method	- Existing equipment can be used - Smaller size restrictions	- Machining man-hours for rods (When using polygonal rods) - Fewer applications
Slurry casting method	- Relatively high degree of freedom in core location	- Optical Properties - Few applications

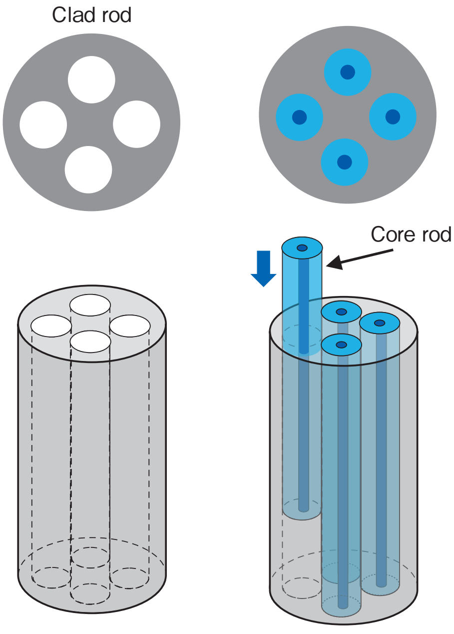

Figure 1 Structure of MCF preform using the drilling method.

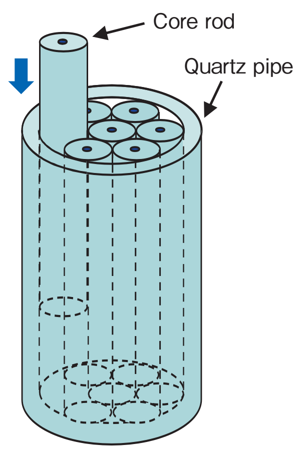

Figure 2 Structure of MCF preform using the stack and draw method.

glass layer, which serves as the cladding, is deposited on a bundle of core rods by an outside deposition method to obtain the MCF preform. The advantages of the over-cladding bundled rods method are that existing manufacturing facilities can be used for outside deposition of the cladding and that there are few restrictions on the size of the preform. The issue is that it is difficult to deposit cladding between the core rods when circular core rods are used. In order to solve this problem, a technique has been reported in which core rods are fabricated into polygonal shapes and targeted by bundling them together[8]. This method has the advantage that the cladding can be deposited uniformly around the core rods, but there is a concern regarding the man-hours required to process the core rods because polygonal core rods are used. In addition, since the over-cladding bundled rods method is a relatively new manufacturing method, there is an issue that examples of its application to MCFs are limited. (Figure 3).

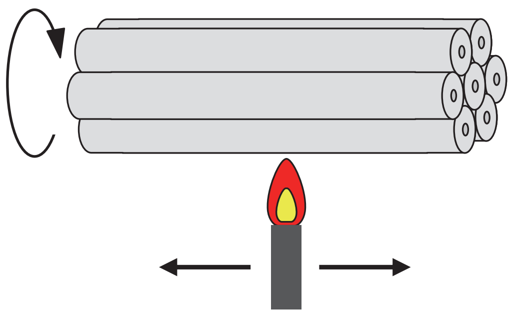

Figure 3 Schematic illustration of the over-cladding bundled rods method.

2.4 Slurry Casting Method

The fabrication of MCF preform by the slurry casting method[9] has also been reported. In the slurry casting method, a liquid slurry is made by adding a curable resin, etc. to quartz powder, which is then poured into a mold to form the MCF cladding material. One advantage of the slurry casting method is that it allows a relatively high degree of freedom in the positioning of the core. The ease of processing makes this method suitable for the fabrication of preforms with many holes. However, the issue is that there are currently only reports of applications to the relatively small preform, and no reports of applications to the large preform. In addition, there are few examples of application to MCF preforms and it is reported that optical properties such as transmission loss are inadequate till now.

2.5 Modified Cylinder Method

In recent years, we have been developing a new manufacturing method for MCFs using a modified cylinder method[10]. In the modified cylinder method, since the cladding material is manufactured using the same manufacturing method as the one that is used for quartz tubes typically in the manufacture of conventional optical fiber preforms, it is possible to increase the size of the preform and to reduce the cost. On the other hand, as with the over-cladding bundled rods method, there are few examples of applications at present, and the technology maturity has to be improved. In the next chapter, we will discuss the modified cylinder method in detail.

3. MODIFIED CYLINDER METHOD

Various methods of manufacturing MCF preform have been studied, but the drilling method is currently the most widely used. As described in Section 2.5, we are developing a new modified cylinder method for MCF preform suitable for reducing processing costs and increasing the size of the preform, which are issues common in the drilling method.

3.1 Design of MCF Preform Using the Modified Cylinder Method

Figure 4 shows the structure of the MCF preform fabricated with the modified cylinder method. In the modified cylinder method, a quartz tube having a cross-shaped vacancy (cross-shaped cylinder) was used as the cladding rod, and four core rods were inserted into the cross-shaped cylinder, and a cladding rod was inserted in the center to form a four-core MCF preform. The cross-shaped cylinder of the modified cylinder method can be fabricated in the same way as quartz tubes used in the preforms of conventional optical fibers, so in principle, it is possible to increase the size of the preform and to reduce the cost. While this design is considered to have excellent manufacturability because it uses fewer components and simplifies the assembly process, there are concerns regarding core misalignment and core non-circularity after drawing the MCF preform because of the large gap between the core rod and the cladding rod in the vacancy of the cross-shaped cylinder.

Figure 5 shows a design that reduces the gap in the MCF preform made by a cross-shaped cylinder. In this design, filler rods of different diameters were newly inserted in order to reduce the gap between the cross-shaped cylinder, the core rod, and the cladding rod inserted in the center. As a result, the gaps are significantly reduced, and the core pitch deviation and the core non-circularity are expected to be reduced. On the other hand, it is expected that manufacturability will be compromised due to the increase in the number of components used and the complexity of the assembly process. Figure 6 shows the design of MCF preform using a cross-shaped cylinder with an optimized vacancy shape (modified cross-shaped cylinder) to achieve both reductions of gaps and of manufacturability. In this design, four core rods and one cladding rod are used to construct the MCF preform, which has excellent manufacturability due to the small number of components used and the simple assembly process. As a result of optimizing the shapes of the modified cross-shaped cylinder, core rods, and cladding rods inserted in the center, the gaps are significantly reduced, and the core pitch deviation and the core non-circularity are expected to be reduced.

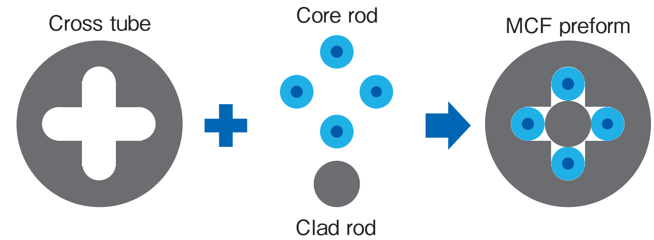

Figure 4 Design of MCF preform using the cross-shaped cylinder.

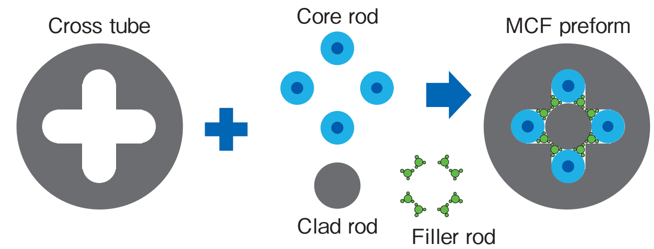

Figure 5 Design of MCF preform using the cross-shaped cylinder with a low gap ratio.

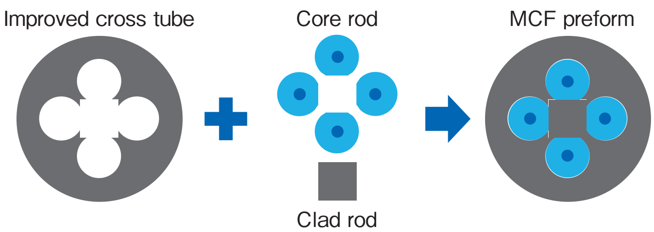

Figure 6 Design of MCF preform using the modified cross-shaped cylinder.

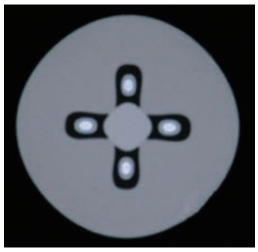

Figure 7 Cross-sectional picture of MCF fabricated using the cross-shaped cylinder.

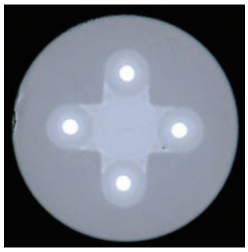

Figure 8 Cross-sectional picture of MCF fabricated using the cross-shaped cylinder with filler cladding rods.

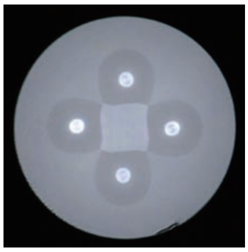

Figure 9 Cross-sectional picture of MCF fabricated using the modified cross-shaped cylinder.

3.2 Characteristics of MCFs Fabricated Using the Modified Cylinder Method

Four-core MCFs were fabricated using the preform processed with the modified cylinder method with the designs shown in Figures 4-6. Pictures of the end faces of the fabricated MCFs are shown in Figures 7 to 9. As shown in Figure 7, the MCF fabricated using the cross-shaped cylinder MCF preform had a large core non-circularity. On the other hand, as shown in Figures 8 and 9, the core non-circularity was significantly reduced in MCFs fabricated from MCF preform with the reduced gaps. The core pitch deviation and the core non-circularity of the MCFs in Figures 7 to 9 were 9.2 μm, 2.3 μm, 1.7 μm, 20.0%, 2.1%, and 1.1%, respectively, when the core pitch deviation from the design value and the core non-circularity were calculated.

Table 2 shows the characteristics of the prototype MCFs. In the cross-shaped cylinder, the transmission loss increased significantly due to the large core non-circularity. Both the reduced gap cross-shaped cylinder and the improved cross-shaped cylinder used cores equivalent to G.652, but the reduced gap cross-shaped cylinder showed an increase in attenuation compared to the normal SMF. The increase in attenuation can be attributed to the effect of stress applied to the core during fabrication in addition to the non-circularity of the core. On the other hand, the attenuation in the modified cross-shaped cylinder with optimized preform design was similar to that of the conventional SMF. These results indicate that the use of the modified cross-shaped cylinder can improve the properties of MCFs without compromising the manufacturability of the preform.

Table 2 Characteristics of MCFs fabricated.

	Cladding diameter (μm)	Core pitch (μm)	Attenuation (dB/km)
Cross-shaped cylinder	124.9	35.8	0.853
Reduced gap cross-shaped cylinder	124.8	42.7	0.412
Improved cross-shaped cylinder	124.9	38.2	0.190

4. CONCLUSION

In this report, we introduced the research and development trend of MCF manufacturing technology being considered from the viewpoint of improving manufacturability for the practical use of MCF. Also, we stated that the drilling method is currently the most widely used manufacturing method because of its high degree of freedom in core positioning and positioning accuracy, and about the associated issues that need to be addressed in the drilling method (drilling costs and restrictions on preform size) for the practical application of MCFs. In addition, we reported on the manufacturing technology of MCF using the modified cylinder method, which we are developing as a new manufacturing method in order to solve the problems of the drilling method. The cross-shaped cylinder for the modified cylinder method can be manufactured with the same manufacturing method as the quartz tube used in the manufacture of conventional optical fibers, so it has the advantage that the size of the preform can be increased and the cost can be reduced. On the other hand, there are still few examples of application to the MCF fabrication because of the new manufacturing method, and the process that satisfies the characteristics of the MCF is still in development. We have optimized the design of the MCF preform using the modified cylinder method and reduced the core pitch deviation and the non-circularity of the MCF. We plan to further develop technologies to improve the manufacturability of MCFs for practical use in the future.

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REFERENCES

1) J. Sakaguchi et al.: “19-core fiber transmission of 19x100x172-Gb/s SDM-WDM-PDM-QPSK signals at 305Tb/s,” OFC2012, PDP5C.1.
2) J. Sakaguchi, et al.: “19-core MCF transmission system using EDFA with shared core pumping coupled via free-space optics,” Opt. Express, Vol.22, Issue 1, pp. 90-95, 2014.
3) D. Soma, et al.: “10.16 Peta-bit/s Dense SDM/WDM transmission over Low-DMD 6-Mode 19-Core Fibre across C+L Band,” ECOC2017, Th.PDP.A.1.
4) G. Rademacher, et al.: “10.66 Peta-Bit/s Transmission over a 38-Core-Three-Mode Fiber,” OFC2020, Th3H.1.
5) T. Matsui, et al.: “Design of 125 um cladding multi-core fiber with fullband compatibility to conventional single-mode fiber,” ECOC2015, We1.4.5.
6) T. Gonda, et al.: “125 μm 5-core fibre with heterogeneous design suitable for migration from single-core system to multicore system,” ECOC2016, W.2.B1C.
7) I. Ishida, et al.: “Possibility of Stack and Draw process as Fabrication Technology for Multi-Core Fiber,” OFC2013, OTu2G.1.
8) R. Fukumoto, et al.: “Multi-core Fiber Fabrication in OverCladding Bundled Rods Method Applying Polygonal Rods,” OECC2019, TuC3-1.
9) J. Yamamoto, et al.: “Fabrication of Multi-Core Fiber by using Slurry Casting Method,” OFC2017, Th1H.5.
10) M. Takahashi, et al.: “Multicore Fiber Fabricated by Modified Cylinder Method,” OFC2020, Th2A.17.