MCF Manufacturing

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Abstract: To actually apply MCFs in the real systems, we still have several challenges to overcome. One of them is the MCF manufacturing technology including measurements and we will describe the current situations and future prospective.

1. Introduction

Recently, space division multiplexing (SDM) using multi-core fibers (MCFs) and/or few-mode fibers (FMFs) is recognized as a strong candidate to overcome the future capacity-crunch [1] and >10 Pb/s transmission using few-mode multi-core fibers have been demonstrated [2, 3]. However, using modes, including coupled core fibers utilizing super modes, still largely increases the complexity of the optical properties measurements, in other words, ensuring optical properties for shipping, as well as the system configurations, partly due to the drastic changes of optical properties by the conditions, such as bending, twist, tension, and so on. One relatively straightforward way to increase space efficiency is increasing capacity uncoupled cores and uncoupled >100-core fibers have been demonstrated in laboratories experiments [4-6]. Besides, uncoupled 4-5 core fibers with a standard cladding diameter, namely 125 μm, are also actively investigated for more-near-future practical applications [7, 8]. The manufacturing technology is one of the key technologies to promote the wide-spread use of the 125 μm MCFs. Here, we introduce the recent activities on manufacturing technologies of MCFs, especially for 125 μm uncoupled MCFs.

2. Fabrication method of multi-core fibers

As for the fabrication method of MCFs, several approaches have been proposed as shown in Fig.1. At this moment, the drilling method is the most actively investigated and relatively matured compared to others. More than few hundred km drawing experiments have been demonstrated [9]. However, drilling method still have several issues. (i) We have to literally drill and remove the cladding material, meaning we waste some materials of the cladding glass. It is concern especially for the ultra-low-loss silica-core type fibers where the claddings require dopants to reduce the index level, typically Fluorine, and higher price than normal silica claddings. (ii) Length of the preform is limited by the drilling length, which has been advanced but still has limitation. (iii) We need an additional process to insert the core rods into the drilled cladding glass and unify the core rods and the drilled cladding by heat treatments either before or during drawing the fibers. That is an additional necessary process required for the drilling method. Investigations to solve these issues have been actively performed and expected to be continuously improved but not perfectly solved yet at this moment. The stacking method solve some problems such as limitations of the drilling length and have been actively investigated as well. However, it increases the complexity even more because we need to prepare the spacers (small) rods in order to fill the gaps generated by stacking the core rods, and need to stack the spacers rods into the gap, basically manually. The stacking method also require the additional unification processes as well. The modified cylinder method also might alleviate the limitation of preform length imposed from the drilling length but we again need to prepare a spacer in the center even though the required spacers rods will be much less than the stacking method. The additional heat unification process is again unavoidable for the modified cylinder method like previously-mentioned other methods. The slurry casting and the sand method would have potentials to solve several issues which have been described above. Especially, for the sand method, the sand is directly inserted into the jacketing tube and additional processes, such as drilling, stacking, and unifying, will not be necessary. However, these technologies have not been matured enough at this moment, in terms of the preform size and the fiber strength, for example, and further investigations would be necessary to apply these in a commercial base. The final method, the cladding synthesis technology, is actually the most similar technologies as conventional fiber fabrication technologies, which have been well established after the long-term optimizations. We need some special equipment or jigs to hold core rods in the beginning but other approaches after holding would be more or less similar as the conventional mass-produced chemical soot deposition technologies. Therefore, this method has the merit in terms of the highest similarities with those of the conventional fibers. However, it has been reported this method also has an issue, namely residual or reminded air gaps after the deposition. This is caused by preventing the soot to be deposit on the core rods because the soot attached to the front core rods and could not go further. It might be solved by the further process optimizations or actively utilize the reminded air-holes to suppress the crosstalk (XT) so it is a very attractive fabrication method of MCFs.

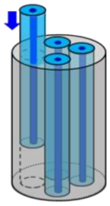
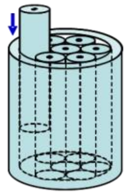
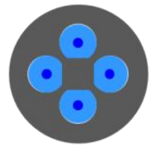
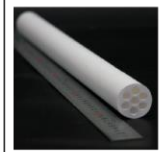
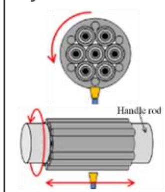
Method	Drilling [9] 	Stacking [10] 	Modified cylinder [11] 	Slurry casting [12] 	Sand cladding method[13] 	Clad synthesis [14] 
Issue	☆We have to waste the silica material by drilling. ☆Length of drilling is limited at this moment. ☆Additional heat treatment is necessary	☆We have to prepare many spacers to stabilize the position of the cores. ☆Additional heat treatment is necessary	☆We have to prepare a square rod placed in the center. ☆Additional heat treatment is necessary	☆The process is not matured enough at this moment. ☆Additional heat treatment is necessary	☆The process is not matured enough at this moment.	☆The jig to position the cores is necessary. ☆Some reports said interstitial spaces often appeared.

Fig.1 Fabrication methods of MCFs

3. Manufacturability of the MCFs

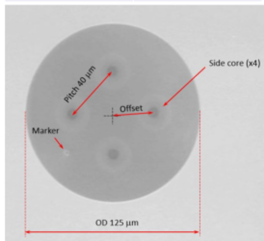
To discuss manufacturability of MCF, it seems to be good to start with which parts of processes and factors are different from the well-established conventional 1-core fibers. It is shown in Table 1 and we can figured out differences exist in the material, the cladding fabrication, the evaluation, and the yield. Note we may need additional processes for fiber drawing as well in some cases but assume the unification process has been done before drawing, here. (i) As for the material, we have to waste some high-purity cladding material by removing it by drilling as described in the previous chapter. At the same time, MCFs have a merit to reduce cladding glass and coating materials because one cladding and one coating material provide M cores, corresponding 1/M required material compared to the conventional 1-core fibers. (ii) As for the cladding fabrications, the drilling and stacking methods require the additional processes, such as drilling, preparing the spacers rods, stacking, unifying by the heat (might be possible to do during drawing which may help to reduce the additional process), and so on. (iii) The optical properties evaluations of MCFs, which obviously require much more complex procedure compared to the conventional SMFs, are another headache for MCFs mass-productivities. It might be somehow alleviated by measuring optical properties, such as OTDR loss, dispersion, PMD, cutoff wavelength, XT, and so on, after connecting with FIFOs. Still, some properties, such as MFD and spectrum loss might be difficult to measure with FIFOs, but FIFOs would definitely help to reduce the evaluation time for MCFs. (iv) The final but savior issue is yield would get worse to the Mth-power unless the yield of each core is not 100%. If the yield of each core is 90%, the yield of 4 core will be 0.9^4 = 66% which potentially would give a big shade in terms of manufacturability of MCF. Increasing the yield of each core will be one, or only, way to overcome this issue.

Table 1. Difference of manufacturing approaches for M-core fibers to 1-core fiber and MCF and merit and demerit

	to 1-core	Merit	Demerit
Material	Different	We can reduce glass and coating material to draw 4 cores at 1 time	We waste the removed cladding material in the case of drilling
Core preform fabrication	Same		
Clad preform fabrication	Different		We need an additional heat treatment for the unification
Drawing	Same		(May need additional process)
Evaluation	Different		We need an additional alignment procedure to put the light
Yield	Different		Yield gets worse to the Mth power for M core

Parts of these issues, however, can be alleviated by enlarging preform size. As for the trials to enlarge preform size of MCFs, one promising result has been realized by the OFS group. The obtained results for 1,800km (in total) 4-core fibers drawn from one 1,800km-size preform are shown in Fig.2. As shown in the Fig.2, very promising results have been obtained keeping very low break rate of 3.4 breaks/fMm. Another approach to solve these issues is using the novel fabrication method, which does not require any drilling or stacking. Using air-hole structures, which improve not only XT but potentially also fabrication process complexities, might be another interesting approach but, of course, we also need to take another complexity of controlling the structure during drawing into account. As for the reducing time for the measurements, a promising result to reduce the splicing loss and splice time using a novel algorism and method was also reported [15].

Parameters	Value
Preform size	1,800 km
250μm Fiber	1,200 km
200μm Fiber	600 km
Break rate	3.4 breaks/fMm



Parameters	Core #1	Core #2	Core #3	Core #4
MFD at 1310 nm, um	8.3	8.3	8.4	8.3
MFD at 1550 nm, um	9.3	9.3	9.5	9.3
Attenuation at 1310 nm, dB/km	0.34	0.35	0.34	0.34
Attenuation at 1550 nm, dB/km	0.19	0.19	0.19	0.19
Zero dispersion wavelength, nm	1315.5	1314.8	1316.0	1314.5
Zero dispersion slope ps/(nm^2 × km)	0.0862	0.0864	0.0865	0.0862
Averaged cabled cut-off, nm	<1260			
Average core pitch, um	40.0			
Average core offset, um	28.3			
Average clad OD, um	124.9			
Average coating OD (uncolored), um	196.8			
Tensile proof test, kpsi	100			
Macrobending attenuation, dB	Meets G.657.A2			
Microbend added loss at 1310, dB/km	<0.12			
Microbend added loss at 1550, dB/km	<0.15			
C-band crosstalk, dB/km	≤ -72			
O-band crosstalk, dB/km	≤ -42			
PMD coefficient, ps/√ km	<0.04			

Fig.2 Promising results to enlarge the size of MCFs preform investigated by OFS (Roman Shubochkin, Alan McCurdy, Tom Liang, Yi Sun, Victor Cusanello, Henson Toland, David Braganza)

4. Conclusions

Uncoupled 4-5 core fibers with a standard cladding diameter have a good chance to achieve the practical use. To realize the wide-usage of the MCF, the manufacturing technology will be one key point. Many fabrication methods have been proposed but all of them have pros and cons. The most well-investigated technology is the drilling method, but it has the issues in terms of additional process, wasting material, and so on. These issues can be alleviated by enlarging the preform size for a certain degree and a promising research result, 1,800km MCF preform drawing, has been demonstrated by OFS. Another concern for mass productions, measurement time, also can be alleviated by using FIFOs. Splicing technologies required for these measurements are also greatly advanced recently.

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