Record length of 2000 km weakly-coupled 7-core MCF produced from a single large-scale MCF preform

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Abstract: We present the design and fabrication of more than 2000 km of a 7-core multi-core fiber (MCF) drawn from a single large-scale MCF preform. The fiber was fabricated without any online fiber breaks and exhibits axially excellent geometrical conformity. First fiber measurements are discussed. This work demonstrates the upscaling potential to pave the way for cost-efficient MCF production.

1. Introduction

In recent years, the demand for high-speed and high-capacity data transmission has become increasingly critical, fueled by the exponential growth of data-intensive applications [1]. Single-core optical fiber (SMF) technology, which has been the backbone of long-distance communication for decades, poses limitations in terms of capacity and scalability. To address these challenges, multi-core fibers (MCFs) have emerged as a promising solution. Multiple cores are incorporated, scaling fiber capacity by adding further signal paths in the spatial domain.

In the past decade, many research activities in the field of spatial division multiplexing (SDM) demonstrated the huge potential of MCF to address the increasing capacity demand in the near future. However, to make the step from academia to new market solutions, the whole MCF ecosystem needs to improve cost efficiency, competing against the well-established single-core fiber standard. Producing a cost-efficient MCF as the key element of SDM solutions is crucial. With the raw material cost scaling only slightly with number of core rods and their Germanium content for MCF over SMF, the additional MCF manufacturing process steps are the main driver to reduce overall production cost. Due to additional process steps for MCF, the scaling of batch sizes is an even more effective way than for SMF to improve cost efficiency [2].

Several fabrication techniques for MCF have been reported in the past [3]. While some methods, such as the slurry casting method or the sand cladding method have not matured yet, the stack and draw approach is limited to smaller batch sizes and is prone to contamination due to many open interfaces within the assembly. In contrast, the drilling approach of cladding cylinders, inserting core rods (CRs) into a drilled MCF cylinder during the assembly stage, offers easy scalability. Additionally, this approach benefits from a potentially very large diameter of the starting preform, as the small relative drilling precision error translates into an excellent geometrical accuracy of the core positions in the drawn fiber, thus reducing splicing losses of propagated light to a minimum. In 2023, Kajikawa et al. applied the drilling approach to fabricate a 4-core MCF with a record length of more than 600 km [2].

In this paper, we report on a MCF production based on a preform batch size yielding more than 2000 km of fiber. This is, to the best of our knowledge, the largest batch size from a single MCF preform run. The fiber was drawn without any online fiber breaks. We demonstrate an excellent geometrical conformity as well as in-spec fiber performance throughout the run.

2. Development of 7-core MCF

2.1. Fiber Design

The design of the MCF has been developed for the scenario of a short-reach PON application with link lengths up to 20 km. The short link length allows for a smaller signal wavelength in the lower end of the O-band (1260 nm-1310 nm). Accordingly, the weakly-coupled MCF facilitates 7-cores in a hexagonal arrangement without the need of a trench. The target specs of the fiber, defined by the application scenario, are a maximum XT of -43 dB/km (i.e. <-30 dB per 20 km link length), a cable cut-off of <1240 nm, a MFD of (8.7-9.2) µm at 1310 nm, a Dispersion range of -8 ps/nm/km $< D_{1260nm} < -3$ ps/nm/km and a standard outer diameter (OD) of the fiber of 125 µm.

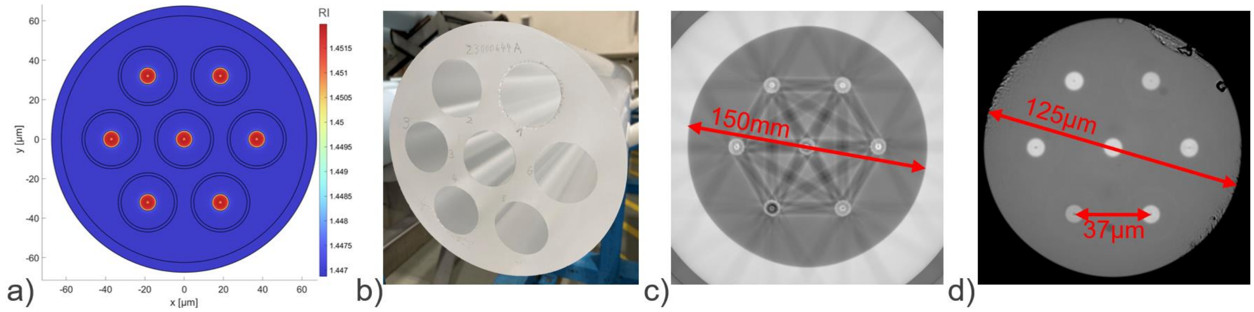

Fig. 1: Development process of 7-core MCF. Graph a) shows the generic target RI profile as studied with FEM modelling. Image b) depicts the drilled cladding cylinder at OD 188 mm. Part c) illustrates RI measurement of the fabricated MCF preform. Image d) shows a microscope image of the drawn fiber.

The fiber design has been developed with an in-house FEM modelling tool for MCF. It is based on commercial 652.D/657.A1 CRs with a diameter of 40.5 mm. The resulting design is illustrated in Fig. 1 a) showing the generic 2D-refractive index profile. The fiber core-pitch Λ is 37.0 µm balancing XT suppression (modelling result: -49 dB/km at 1260 nm) and leakage loss of outer cores (<0.01 dB/km).

2.2. Preform and fiber fabrication

The fabrication of the MCF preform is based on Heraeus in-house cylinder drilling technology. The angular and radial position of the bores can be independently adjusted within the cladding cylinder. Hence, the core pitch Λ is decoupled from other geometrical parameters, such as the core size and fiber-OD, simplifying the design process compared to the stack and draw approach. Furthermore, the large-scale drilling ensures highly precise core positions in the resulting fiber. The positioning of the bores is better than 0.05 mm deviation from the target position and the axial deflection is less than 0.3 mm over 1500 mm of drilling length. This translates to a position accuracy of the cores better than 0.2 µm in a 125 µm fiber. Such a high position accuracy is the basis to realize tight design specs and ensure low splicing losses when combining fiber segments from different batches. Additionally, with a surface roughness of Rz<2 µm in bores, the applied drilling process allows for pristine surface quality, reducing interface failures and lowering break rate issues.

The production of the developed fiber design (Fig. 1 a) has been realized with the drilling approach, following the steps similar as in [2]. Matched to the CRs, an OVD cylinder with OD 188mm and ID 42mm (central hole) has been drilled according to the design targets. With a matched drilling diameter of 42 mm, the outer holes have the same size as the central hole. The drilled MCF-cladding cylinder with 7 holes is illustrated in Fig. 1 b. While the MCF-cladding cylinder would be sufficient to produce >3000 km of MCF, the available CR material limited the batch size of the run.

In the next step, the MCF-cladding cylinder is assembled with the CRs and consolidated to a MCF preform. Crucially, the CR OD was matched close to the diameter of the holes, ensuring small air gaps for lower geometrical distortions of the cladding and the cores during preform drawing. A tomographic RI profile (RIP) measurement of the realized MCF preform at OD 150 mm in Fig. 1 c confirms the excellent geometrical conformity with negligible core deformation. Important to note, the measurement in Fig. 1 c suffers on material-induced measurement artifacts causing parasitic shadow rays.

In the last step, the MCF preform has been drawn at 2.5 km/min to a fiber with 125 µm OD. The drawing yielded 2061 km of MCF, demonstrating, to the best of our knowledge, a new record in batch size. Remarkably, no online fiber breaks occurred indicating excellent mechanical properties and robust fiber drawing.

3. Results of first measurements

A basic analysis of the developed MCF has been conducted subsequently to the fiber drawing. Focus was put on the axial geometrical conformity of the MCF. Fig. 2 shows three microscope images (with arbitrary orientations) of the fiber cross-section: one close to the start of the run (Fig. 2 a), one from the middle (Fig. 2 b) and one close to the end (Fig. 2 c). The pictures already indicate an excellent geometrical conformity from start to end. While the cladding shows some mild 6-fold deformation on the outer side, following the core positions, the cores appear without noticeable non-circularity. The different brightness in each core is a consequence of the rudimentary illumination setup. A detailed analysis of the images enables key geometrical parameters to be tracked along the drawing run.

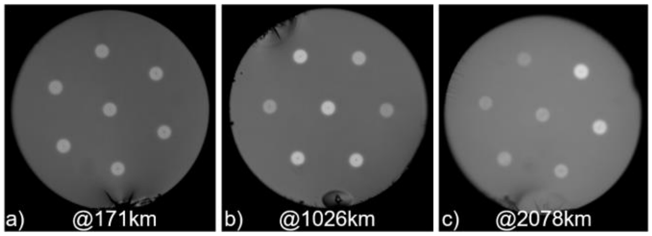

Fig. 2 shows microscope images of the drawn MCF at different accumulated drawing positions. Image a) shows the cross-section close to the start, b) in the middle and c) close to the end of the run.

The results are listed in Table 1. From the fiber drawing records, the OD for each sample is included, being slightly above the targeted 125.0 µm. Highlighting the core-pitch Λ (averaged for the outer cores) as the key parameter, the measurement matches excellently the targeted value of 37.0 µm. Axial variations cannot be resolved within the accuracy of the measurement, proving excellent geometrical conformity. Such accurate core positions are the key to achieve low splicing losses as well as to realize tight specs in MCF design.

Table1. Summary of fiber measurements for 3 axial positions. Optical parameters are measured in the central core.

	Design Target	**Start**	**Middle**	**End**
Accumulated Fiber Pos. [km]		171	1026	2078
Rel. Fiber Position [%]		**8%**	**48%**	**97%**
Fiber-OD [µm]	*125.0*	125.1	125.1	125.2
Avg. Core Pitch Λ [µm]	*37.00*	**37.01 ± 0.16**	**37.02 ± 0.10**	**37.08 ± 0.23**
Avg. Outer Clad. Thickn. [µm]	*25.50*	25.54	25.52	25.51
Fiber Curl [m]	*>4*	9.7	16.2	21.9
Attenuation 1310nm / 1385nm [dB/km]	*<0.38 / <0.35*	**0.329** / 0.278	**0.330** / 0.278	**0.329** / 0.278
Cable Cut-off - central core [nm]	*<1240*	1238	1219	1210
MFD_{1310nm} [µm]	*(8.7-9.2)*			9.04

Optical properties of the MCF have been measured for the central core with standard telecom fiber metrology. All studied parameters are well within the design targets and remain consistent along the run. The attenuation at 1310nm matches typical values of standard telecom 652.D fibers, indicating no penalties due to the additional processing steps for the MCF geometry.

Further measurements on the optical characteristics, especially on the XT and leakage loss, will be done soon.

4. Conclusions

We have demonstrated the up-scaling potential of MCF fabrication using the drilling approach of a cladding cylinder and subsequent stacking of CRs. A record-length MCF with more than 2000 km has been drawn from a single MCF preform without any online fiber breaks. A geometrical analysis confirmed excellent accuracy in the core position, showing no axial drift in the pitch within the measurement resolution of about 0.2 µm. Furthermore, first measurements indicate excellent optical properties, most prominently a very good attenuation at 1310 nm. Further measurements on typical MCF characteristics will be done soon.

These results demonstrate maturing of multi-core fiber technology in a serial-production scale process. This leads us to believe that the fiber itself should be able to support a commercially viable solution in the future. Within the rather cost-sensitive short-range PON environment, implementation of seven cores seems a good compromise between optimization by scaling and achieving good optical propagation characteristics, within a fiber OD of 125 µm. Next steps could be field tests of competing core layouts and underlying production processes, and successive standardization. Now, we believe the biggest hurdle for an adoption of MCF technology is the connection of MCFs to transceivers used in this environment. We expect that development of such connections may also be driven by the adjacent application field in data centers, specifically artificial intelligence. Research activity in optical integration and densification has increased recently, and we see substantial potential of MCF technology to also contribute here.

Acknowledgements

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