Uncoupled 6-core Fibers with a Standard 125-μm Cladding, ITU-T G.652 Optical Properties, and Low XT

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Abstract: We developed ultra-high-density uncoupled 6-core fibers with a standard 125-μm cladding, G.652 properties, and low crosstalk at 100 km of -55~-39 dB by utilizing a novel air-gap structure, which would potentially give the ultimate high-density.

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]. Recent progress in this area enabled >10 Pb/s transmission using few-mode MCFs [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, as well as the system configurations, partly due to the drastic change of optical properties by the conditions, such as bending, twist, and so on. One relatively straightforward way to increase space efficiency is increasing the number of uncoupled cores, and >100-core fibers have been demonstrated in this direction [4-6]. However, these fibers have been realized with cladding diameters larger than the standard cladding diameter. Keeping the standard cladding diameter, namely 125 μm, is attractive from the aspect of world-wide, well-established tools for handling and connecting fibers. At present, the number of cores, realized by using the trench-assisted structure as well as a heterogeneous center core, has been limited to 4-5 to keep C/L-band transmission capabilities [7, 8]. Standard cladding 8-core fibers have been demonstrated but limiting the transmission band to O-band [9]. Here, we demonstrated standard 125-μm-cladding, uncoupled 6-core fibers while keeping G.652 properties, which ensure O to L band transmissions, for the first time, by utilizing a novel structure.

2. Design of the MCFs

As for the basic design concept, we propose a new structure shown in Fig.1 (left), where core rods, comprised of a center core and a surrounding cladding are attached to the outer jacketing tube while keeping air gaps between each homogeneous or alternatively heterogeneous core rod. In particular, the air-gap structure is quite attractive for ultimate high-density since the inter-core crosstalk (XT) is drastically suppressed by the air gap between core rods while higher-order modes (HOMs) are escaped to the direction of the coating. To see the effect of air-gap, 100 km inter-core XT was calculated as a function of core pitch for a step-index (SI) MCF, trench-assisted (TA) MCF and air-gap (AG) MCF where the AG-MCF was modeled to have an air trench surrounding each core rod and the effect of the outer jacketing tube was neglected for simplicity. An example is shown in Fig.1 (center) where the same homogeneous SM core parameters were used. The air-gap structure shows clear advantages in terms of very low XT due to its ultimate low refractive index of the air, ~1.0. In order to break the current limit of 4 outer cores within a 125-μm cladding while keeping standard optical properties, such as ITU-T G.652 properties, we set our target as shown in the Fig.1 (right) where 6 cores are accommodated keeping air gaps between each other.

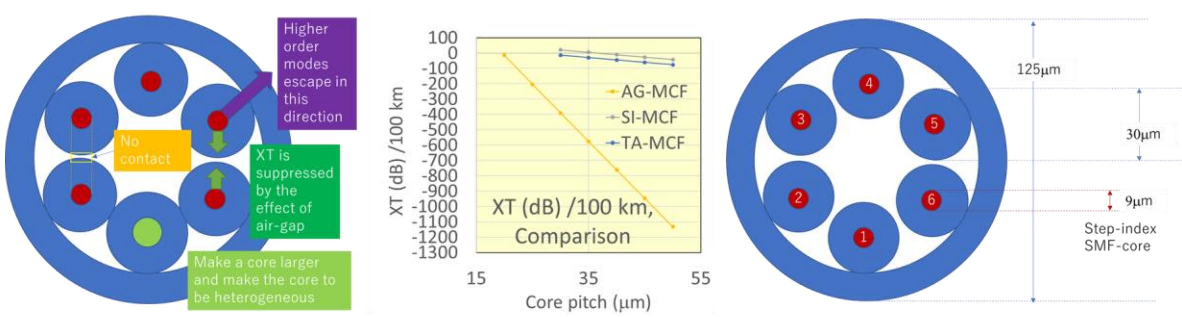


Fig.1 Concept of new structure (left), XT simulation (center), and target structure (right)

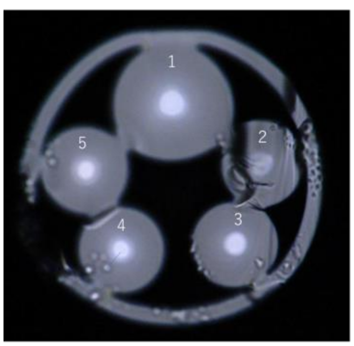
Even though the air gap effectively suppresses the XT between the cores, it has the risk to change the field distribution or increase the cutoff wavelength. Therefore, we optimized the structure and confirmed the A_{eff} and cutoff properties by FEM-based simulations. As shown in Table 1, A_{eff} was a standard value of 80 μm^2, corresponding to MFD of ~10.1 μm, and the air gap does not change field distribution drastically. Cable cutoff wavelength, calculated by the bending loss of LP11 mode, showed relatively low value of ~1060 nm. However, it should be noted that calculation was performed when the fiber was bent to the outer-side (coating) direction. The leakage loss of the fundamental mode bent at a bobbin diameter (assumed 280 mm diameter, this time) was quite low by the effect of the new structure, but perturbations such as bending and twisting may change the optical properties. The real cutoff, as well as a leakage loss of the fundamental mode, should be statistic values and need to be confirmed experimentally as well, but the promising results have been confirmed. Calculated XT at 100 km transmissions also showed very low value.

Table 1. Optical properties obtained by the simulations at 1550 nm

Properties	neff	Aeff	MFD	Cable Cutoff	Leakage loss (140mmR)	XT at 100 km
[unit]		[μm^2]	[μm]	[nm]	[dB/km]	[dB]
Value	1.447036	80.2	10.1	1059	0.00058	-63.9

3. Experimental studies

We fabricated a ~125-μm-cladding, 5-core fiber to confirm the effect of air-gap as well as the heterogeneous-core arrangement, which would be also realized relatively easily by preparing different-size core-rods. The obtained structure and optical properties are shown in Fig.2. The measured attenuation loss, mode-field diameter (MFD), and cutoff wavelength are almost as expected. The LP11 mode seems to successfully escape to the direction of the coating. The XT at 100 km between core 3-4 was very low of <-40 dB, which is much lower than that of an all-solid SI-MCF with the same core index structure of about -17 dB. The heterogeneous core, together with the effect of the larger core pitch and, probably a little distorted core shape for core-1, improved the XT properties but sacrificing the space efficiency. This time, we intentionally used a thinner jacketing tube to see the effect of the leakage loss, but spectrum loss measured for core 3 and 4 did not show significant loss increase over the wide range of wavelengths, indicating the leakage loss of the fundamental mode was successfully suppressed as expected from the simulations.



Core	Loss [dB/km] @1550nm	MFD [mm] @1550nm	λc [nm]
1	0.225	10.1	1393
2	0.254	9.3	1152
3	0.231	9.4	1153
4	0.261	9.5	1181
5	0.245	9.2	1156

XT@100km[dB]

Core	measurement	simulation
3-4	-41.2	-17.2*
1-2	-54.1	-
5-1	-57.6	-

*Simulation XT is calculated in the case of all solid fibers

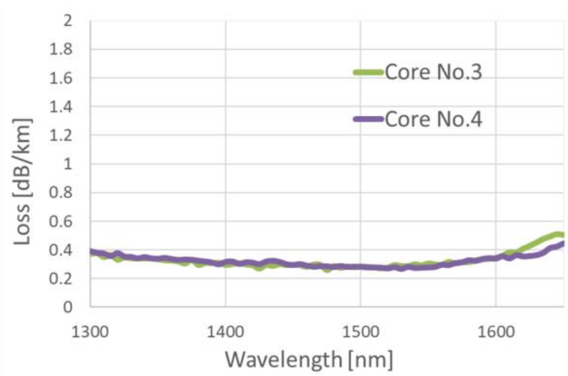
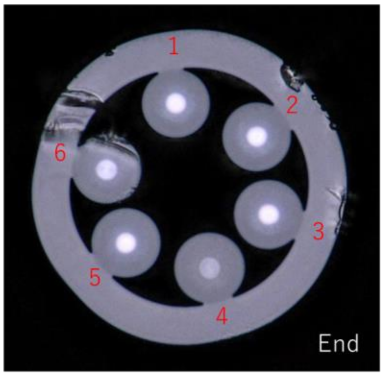


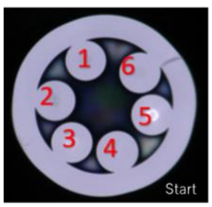
Fig.2 Obtained structure of the 5-core fibers (left) and optical properties including spectrum loss of core 3 and 4 (right)

Then, we fabricated a ~125-μm-cladding, 6-core fiber by a core-rod and jacketing-tube attaching method. The obtained structure and optical properties are shown in Fig.3. As shown in the figure, the structure is well controlled and optical properties are almost as expected. The MFD at 1310 nm is ~8.6 μm, little smaller than the target value, but all properties comply with ITU-T G.652 standard, except for attenuation losses. The loss of ~0.5 dB/km was higher than ~0.25 dB/km of the 5-core fiber described above. The average loss spectrum for the 6 cores did not show any significant increase in a wide range of wavelengths but a little increase at longer wavelengths such as L-band, partly due to the ~10% smaller core rod diameter than the target value of 30 μm. It should be noted the loss spectrum in C-band, which is shown in the inset, showed flat loss properties. XTs were very low, -55 ~ -45 dB at 100 km except for core 5-6, where core rods distance became very close and touched each other in some parts along the length. The higher losses than 5-core fibers as well as higher XTs for the cores 5-6 can be solved by the further design and process optimizations.

In Fig.3 (bottom right), several approaches to further improve the space efficiency are indicated. Of course, one relative straightforward way is simply increasing the number of the attached outer cores. From our simulations, 8 cores should also be possible to keep low XT properties. The other way is placing an additional core rod in the center. In that case, we would not be able to place a gap between the center core rod and surrounding core rods so that we may need to apply a heterogeneous core for the center core. Since we have confirmed the effectiveness of the heterogeneous core approach for this type of structures with the 5-core fiber, it would give us one additional core, resulting in low-XT, 7-core fibers or 9-core fibers within a 125-μm cladding keeping standard optical properties.

Structure





Cladding Diameter =125.3μm
Length =2.0km

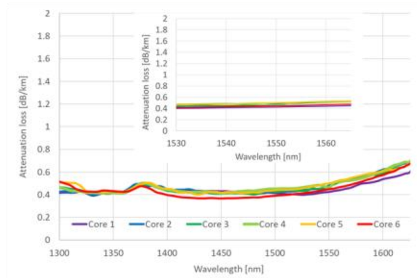
Optical properties

Properties	Value
Attenuation loss @1550nm [dB/km]	1: 0.501 2: 0.524 3: 0.541 4: 0.462 5: 0.515 6: 0.544
Cutoff wavelength @2m [nm]	1: 1233 2: 1214 3: 1235 4: 1301 5: 1256 6: 1287
MFD @1550nm [μm]	1: 9.3 2: 9.3 3: 9.3 4: 9.4 5: 9.3 6: 9.2

100km-XT[dB]

Core	1-2	2-3	3-4	4-5	5-6	6-1
XT	-52.6	-44.4	-43.9	-49.5	-38.7	-54.9

Loss spectrum properties of 6 cores (Inset; Loss spectrum in C-band)



Structures to improve the space efficiency further

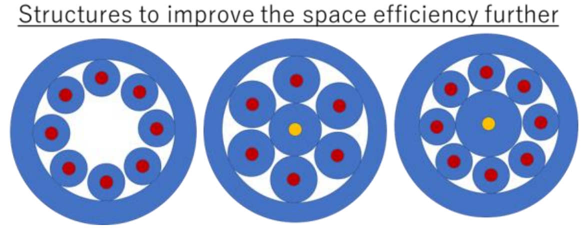


Fig.3 Obtained structured and optical properties of novel 6-core fiber and possible new structures to further improve the space efficiency

4. Conclusions

A standard 125-μm-cladding, uncoupled 6-core fiber keeping ITU-T G.652 optical properties and low 100-km-XTs of -55 ~ -39 dB was realized for the first time by utilizing a novel air-gap structure. The low XT was realized by the effect of air-gap between the core rods while standard optical properties were kept by the effect of novel attached core structure. This new concept and good optical properties were confirmed by simulations and experiments. Further higher densities keeping a standard125-μm cladding, low XT, and ITU-T standard properties should be possible by increasing the number of outer cores as well as by placing a center core rod. We have not accurately identified the limit of this novel structure yet, and much higher ultimate densities might be possible by further optimizing these novel structures in the future.

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