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12-core fiber with one ring structure for extremely large capacity transmission

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Abstract: The feature of a multicore fiber with one-ring structure is theoretically analyzed and experimentally demonstrated. The one-ring structure overcomes the issues of the hexagonal close-pack structure. The possibility of 10-core fiber with A_{eff} of 110 μm^2 and 12-core fiber with A_{eff} of 80 μm^2 is theoretically presented. The fabricated 12-core fibers based on the simulation results realized A_{eff} of 80 μm^2 and crosstalk less than −40 dB at 1550 nm after 100-km propagation. The MCF with the number of core larger than seven and the small crosstalk was demonstrated for the first time.

OCIS codes: (060.2270) Fiber Characterization; (060.2280) Fiber design and fabrication.

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1. Introduction

Space division multiplexing (SDM) is expected as a breakthrough technology against capacity crunch of optical transmission system over a single-mode fiber. Multicore fibers (MCFs) have been developed for a transmission fiber of SDM system [1–9] and the results of transmission experiments had been reported [3,7,10–12]. Almost all the reported MCFs were seven cores with hexagonal close-packed structure (HCPS). The recently reported 19-core fiber was also based on the HCPS [7]. The HCPS has some issues on effective crosstalk [3] and flexibility of the numbers of cores [5]. In addition, the trench-assisted structure, which is recognized as an indispensable technique to suppress inter-core crosstalk, causes another issue on the control of cutoff wavelength [1,4]. We have proposed a two-pitch structure (TPS) as a solution for these issues [5,6].

Recently, the transmission experiment with the record capacity of 1.01-Pb/s over a 12-core fiber has been reported [11]. The 12-core fiber employed novel core arrangement called one-ring structure (ORS). In this paper, the characteristics of the ORS-MCF are presented. After the explanation of the feature of the ORS, the optimization of the ORS by the numerical simulation is presented. The simulation results are confirmed by the characteristics of fabricated ORS-MCFs with 12 cores.

2. Feature of one-ring structure

Figure 1 shows schematic diagram of proposed MCFs. Though the HCPS has been the most popular structure, the HCPS has three issues to be concerned.

1. Core pitch Λ limitation due to lengthening of cutoff wavelength (λ_c) of inner cores [1,4].
2. Excessive crosstalk degradation of inner cores [3].
3. Low flexibility of the number of cores [5].

The TPS is a solution for the second and the third issues. However, the pitch of TPS is still constrained by the cutoff wavelength of a center core [6].

The ORS is free from the 1st issue thank to elimination of a center core. The elimination of a center core is helpful to overcome the second issue related to crosstalk. In the case of the HCPS, the center core has six adjacent cores and the outer cores have three or four adjacent cores. The cores of the ORS have only two adjacent cores. Here, we assume the following conditions:

1. All cores carry equal signal power.
2. Crosstalk between two cores is equal for all combination of adjacent cores.
3. Crosstalk between two cores is small enough.

Under the conditions, the worst crosstalk of the cores is estimated as follows:

$$\mathrm{XT}_{worst} = \mathrm{XT} + 10\log n, \tag{1}$$

where $\mathrm{XT}_{\mathrm{worst}}$ is the worst crosstalk in [dB], XT is crosstalk between two cores in [dB] and n is the number of adjacent cores. The maximum change of crosstalk ΔXT is defined as follows:

$$\Delta \mathrm{XT} = \mathrm{XT}_{worst} - \mathrm{XT}. \tag{2}$$

Table 1 summarizes ΔXT of MCFs with various structures. The ΔXT of the HCPS ranges from 4.8 dB to 7.8 dB. In the case of TPS, The ΔXT of the inner core is 9.5 dB, which is largest value in Table 1. However, the 9.5-dB ΔXT is negligible because the XT between an inner core and an outer core is 30 dB smaller than that between outer cores [5]. The ΔXT of the ORS is 3.0 dB for all cores. Accordingly, we can conclude that the ORS can overcome the second issue.

The third issue is related to the cladding diameter (D_c) limitation related to mechanical reliability. We have proposed 225 μm as an upper limit of the D_c [5]. Figure 2 illustrates the allowable number of core as a function of D_c for HCPS, where core pitch $\Lambda = 40$ μm [13] and cladding thickness (T_c) = 30 μm [2]. The Λ and the T_c are required to realize 100-km XT of −50 dB at 1550 nm at bending radius of 500 mm, effective area (A_{eff}) of 80 μm^2 at 1550 nm without the excess loss of outer cores. $\mathrm{XT}_{\mathrm{worst}}$ is estimated to be about −42 dB. The D_c of 19-cores HCPS is estimated to be 220 μm. The ORS can flexibly arrange the number of cores in accordance with an allowed D_c as demonstrated in the following chapter.

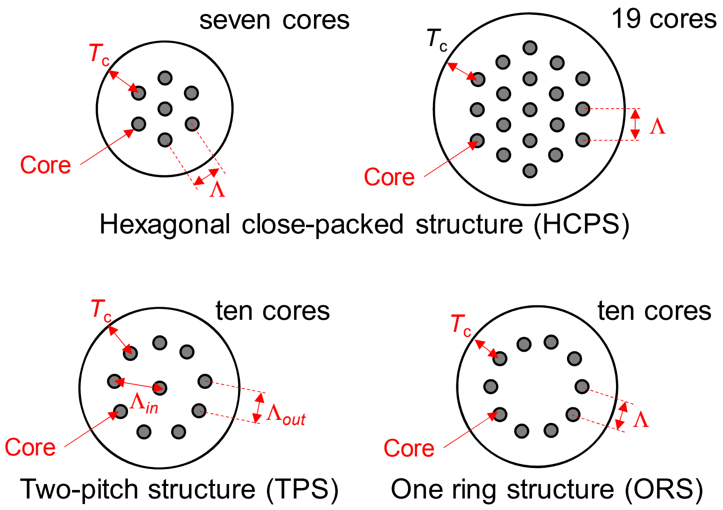

Fig. 1. Schematic diagram of various kinds of MCF.

Table 1. ΔXT for various structures

Structure	HCPS			TPS (10 core)		ORS
Core Position	Inner	Outer		Inner	Outer	-
Number of adjacent core	6	3[1)]	4[2)]	9	2	2
ΔXT [dB]	7.8	4.8	6.0	9.5[3)]	3.0	3.0

1) All outer cores of 7-core layout and corner outer cores of 19-core layout.
2) Side outer cores of 19-core layout.
3) The effect of a center core is negligible because the XT between an inner core and an outer core is 30 dB smaller than that between outer cores [5].

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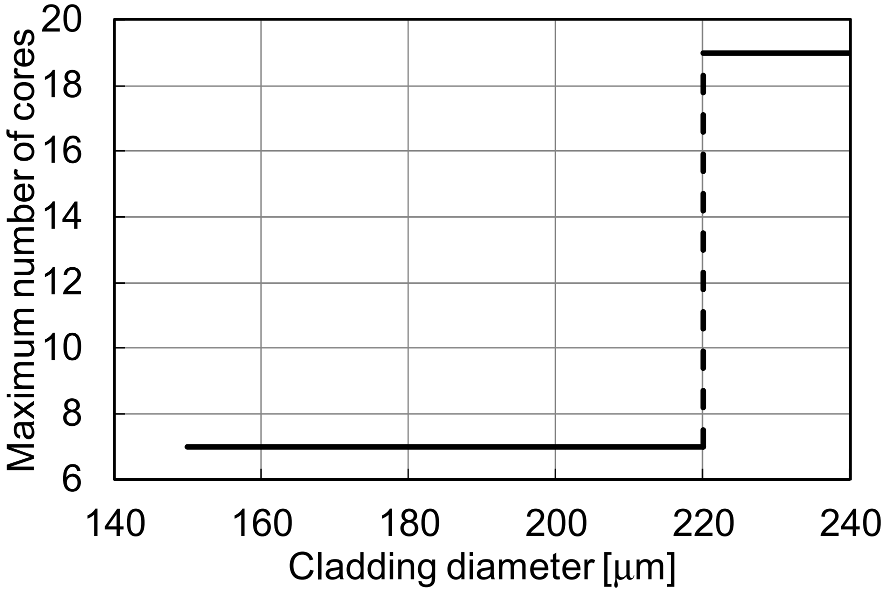

Fig. 2. Cladding diameter dependence of maximum number of cores for HCPS: $\lambda_c = 1.53$ µm, A_{eff} at 1550 nm = 80 µm^2 and 100-km XT at 1550 nm = –50 dB at bending radius of 500 mm. Core pitch $\Lambda = 40$ µm. Cladding thickness $T_c = 30$ µm.

3. Simulation results

We have simulated the expected D_c of ORS-MCF. Full-vector finite element method was used for the simulation [14]. XT with homogeneous cores was simulated with power-coupling coefficient h given by Eq. (25) in Ref [15]. and fiber length L.

$$\begin{aligned} \mathrm{XT} &= \tan\mathrm{h}(hL) \\ &\approx \frac{2\kappa RL}{\beta\Lambda}, \end{aligned} \tag{3}$$

where κ is the coupling coefficient between neighboring cores, R is bending radius, β is the propagation constant of cores and Λ is core pitch. We used $R = 155$ mm for the simulation of ORS-MCF regarding our spool size. Note that the crosstalk of the HCPS shown in the previous chapter was estimated at the bending radius of 500 mm. XT is improved by 5 dB by changing the bending radius from 500 mm to 155 mm. The $\mathrm{XT}_{\mathrm{worst}}$ of the HCPS at the bending radius of 155 mm is estimated to be –47 dB.

A trench-assisted structure shown in Fig. 3 was employed for the refractive index of core to suppress XT [1]. $r_2/r_1 = 2.0$, $w/r_1 = 1.2$, $\Delta_2 = 0\%$ and $\Delta_3 = -0.7\%$. Figures 4(a) and 4(b) represent the simulation results for different A_{eff} range: Fig. 4(a) shows 80-µm^2 range and Fig. 4(b) shows 110-µm^2 range. A cutoff wavelength (λ_c) was defined as the wavelength where the confinement loss of the LP_{11} mode was 1 dB/m. The effective cable cutoff wavelength of single-mode fibers is defined as the wavelength where the LP_{11} mode undergoes 19.3-dB attenuation after 22-m propagation [16]. The LP_{11}-mode confinement loss of 1 dB/m means that LP_{11} mode suffers 22-dB attenuation after 22-m propagation and is good indicator of the effective cutoff wavelength. Dashed lines and dotted lines are contour line of A_{eff} and λ_c, respectively. Colored solid lines represent core pitch Λ contour that realizes XT of –50 dB at 1550 nm after 100-km propagation, which XT is equivalent to $\mathrm{XT}_{\mathrm{worst}}$ of –47 dB for the ORS.

Figure 4(a) indicates that Λ of 36.5 µm is required to realize an ORS-MCF with A_{eff} of 80 µm^2 and cutoff wavelength of 1530 nm. Figure 5 shows the allowable number of cores for ORS and HCPS as a function of D_c, where $\mathrm{XT}_{\mathrm{worst}} = -47$ dB. $\Lambda = 36.5$ µm for the ORS. $\Lambda =$

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40 μm for the HCPS. T_c = 30 μm for both the structures. The ORS allows us to increase the number of cores according to allowed cladding diameter. We can arrange 12 cores in a cladding of 201-μm diameter by using the ORS. In the case of 12-core fiber, the core can also be arranged on a hexagon: six core on tops and six cores on the middle of sides. The D_c with hexagonal structure is 206 μm, which is slightly larger than that of circular structure and is still smaller than that of the 19-core HCPS. We can select an appropriate structure in consideration of fabrication process.

We can derive Λ of 41 μm for 100-km XT of −50 dB, A_{eff} of 110 μm^2 and cutoff wavelength of 1530 nm from Fig. 4(b). 10 cores can be arranged in a cladding of 213-μm diameter including 40-μm T_c [4]. To achieve the same XT_{worst} of −47 dB and A_{eff} of 100 μm^2, Λ is 46.0 μm for HCPS [13] and 47.4 μm for TPS [5]. Small core pitch design is allowed by using the ORS. The cladding diameter of 10-core TPS and 19-core HCPS are estimated to be 219 μm and 264 μm, respectively. The ORS is effective to realize large A_{eff} and low crosstalk MCF with comparatively small cladding diameter.

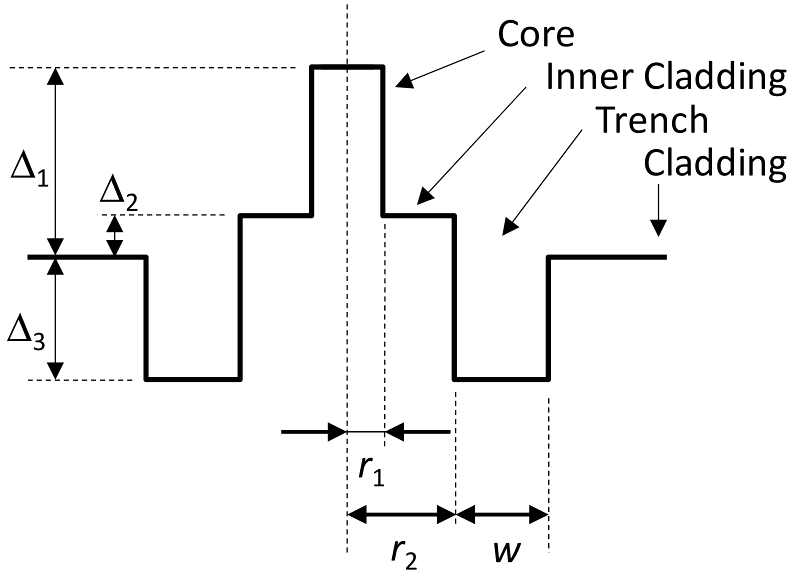

Fig. 3. Schematic diagram of a trench-assisted structure.

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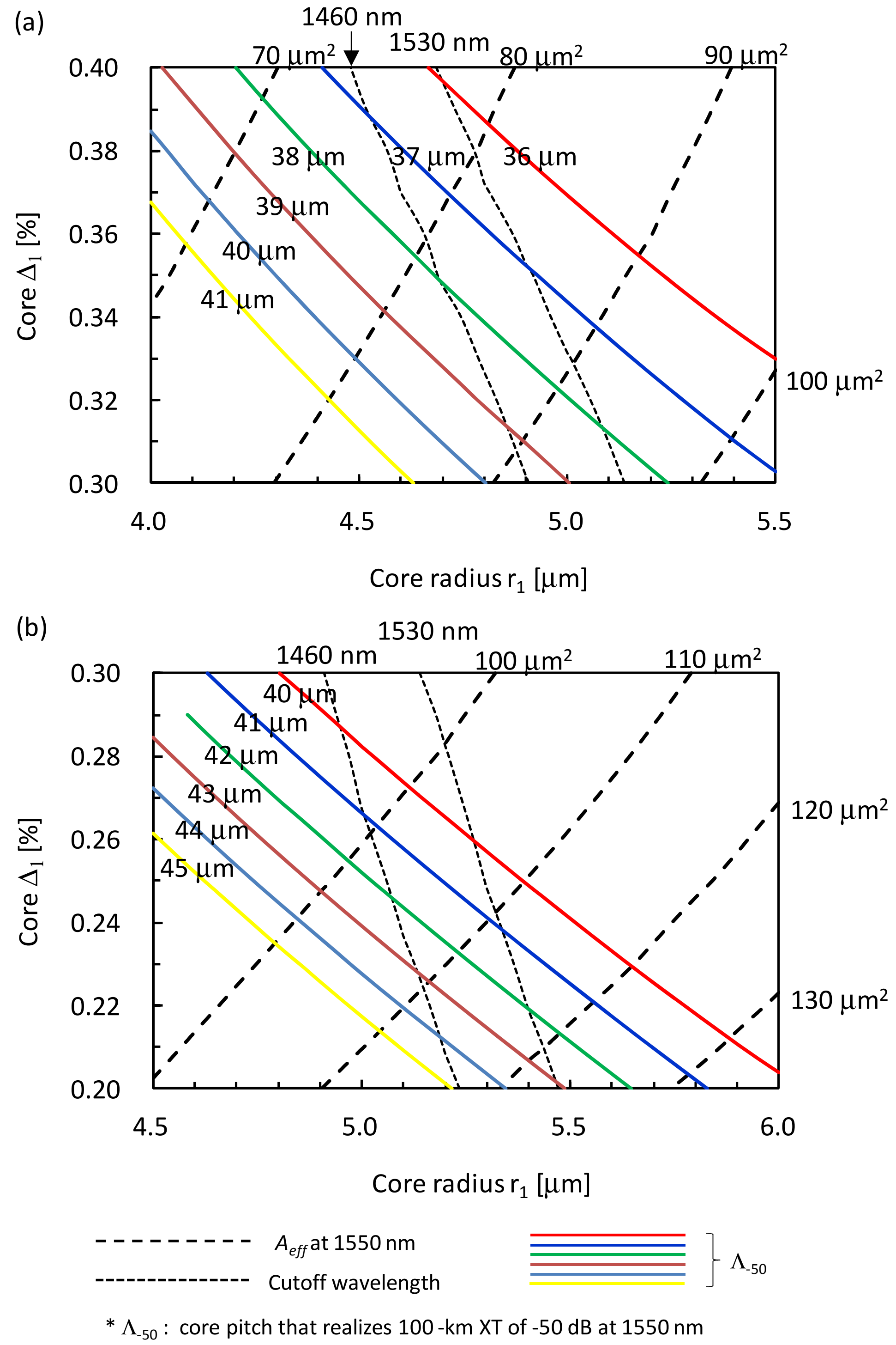

Fig. 4. Structural parameter dependence of A_{eff}, cutoff wavelength and Λ_{-50}.: (a) Results on 80-μm² A_{eff} range. (b) Results on 110-μm² A_{eff} range.

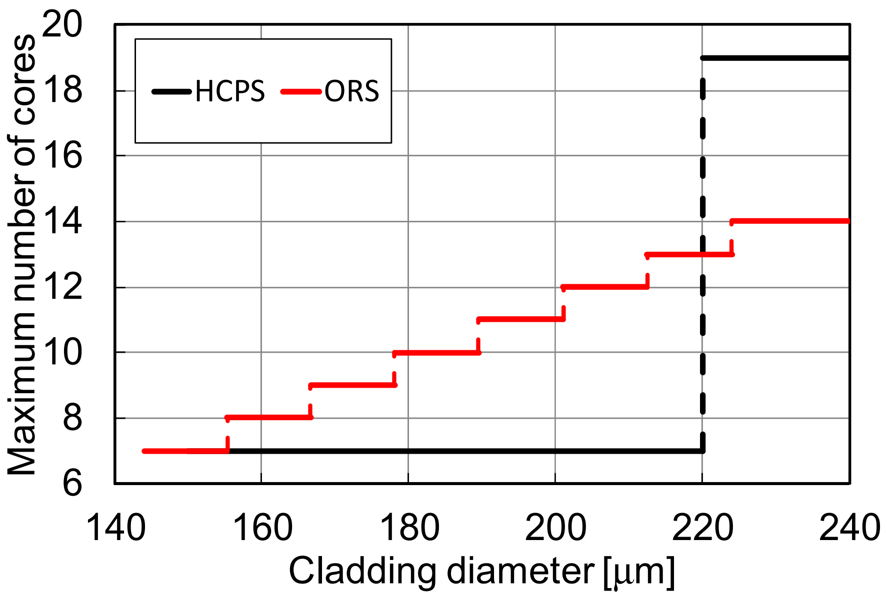

Fig. 5. Cladding diameter dependence of maximum number of cores for ORS and HCPS: λ_c = 1.53 μm, A_{eff} at 1550 nm = 80 μm^2 and 100-km XT_{worst} at 1550nm = –47 dB at bending radius of 155 mm. Cladding thickness T_c = 30 μm. Λ = 36.5 μm for ORS. Λ = 40 μm for HCPS.

4. Measurement results of fabricated fibers

We have fabricated ORS-MCFs based on the simulation. Figure 6 shows cross sectional view of a fabricated ORS-MCF with 12 cores that are arranged on the hexagon. The arrangement of 12 cores on the hexagon is the same with outermost cores of 19-core HCPS as shown in Fig. 1. Accordingly, we could fabricate the 12-core fiber by using the stack and draw method, with which rods are assembled on the HCPS. Two preforms (A, B) were prepared for this experiment. Table 2 summarizes structural parameters and average characteristics of fabricated ORS-MCFs. The alphabet of a fiber ID indicates a preform ID. Λ = about 37 μm and D_c = about 225 μm for the fibers. The D_cs were larger than expected value of 201 μm, which is presented in the previous section, because the T_c of about 39 μm was larger than the minimum required value of 30 μm. Averaged attenuation at 1550 nm was about 0.20 dB/km. A_{eff} was about 80 μm^2 in average. Cutoff wavelength was smaller than 1530 nm for all cores. Table 3 shows measurement results of the fabricated fibers. Measured λ_c and A_{eff} were varied within narrow limit: the fabricated fibers had quasi-homogeneous structure. Figure 7 shows estimated 100-km XT between cores. A 100-km XT was evaluated from measured crosstalk with each length based on length dependence of the XT [17]. XT was measured on a fiber wound on a spool with diameter of 310 mm. Averaged power over 4000 points sampled at 20 msec interval was used for XT calculation. Power variation over the averaging period was 6 dB at a maximum. The 100-km XT at 1550 nm ranged from –41 dB to –48 dB. The average XT at 1550 nm was –45 dB. The 100-km XT_{worst} was estimated to be less than about –40 dB at 1550 nm and about –30 dB at 1625 nm.

Figure 8 shows the relationship between 100-km XT_{worst} and number of cores for single-mode MCFs(SM-MCFs) presented so far. The XT_{worst} was estimated from reported XT with Eq. (1). The MCFs whose number of cores is larger than seven resulted in relatively large XT_{worst} about –20 dB. The fabricated 12-core fibers with the ORS successfully increased the number of cores with the small XT_{worst} of –40 dB at 1550 nm for the first time.

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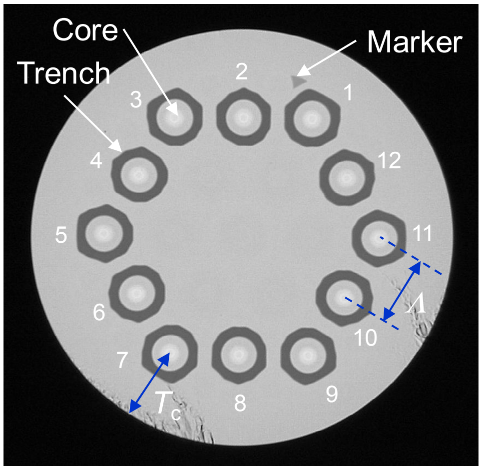

Fig. 6. A cross sectional view of a fabricated 12-core fiber.

Table 2. Structural parameters and average characteristics of fabricated MCFs

Fiber ID		A-1	A-2	B-1
Length	[km]	26.0	27.2	52.5
Λ	[μm]	37.0	36.7	36.8
D_c	[μm]	225.3	225.4	225.0
T_c	[μm]	38.7	39.3	38.9
Attenuation$^{1)}$	[dB/km]	0.201	0.206	0.199
λ_c (22 m) $^{2)}$	[μm]	1.47	1.46	1.47
A_{eff} $^{1)}$	[μm^2]	80.4	80.2	80.7

1) Averaged value for all cores at 1550 nm.
2) Averaged value for all cores.

Table 3. Measurement results of fabricated MCFs

Fiber A-1

	Attenuation at 1550 nm [dB/km]	Attenuation at 1625 nm [dB/km]	λ_c (22 m) [μm]	A_{eff} at 1550 nm [μm^2]	A_{eff} at 1625 nm [μm^2]
1	0.199	0.206	1.51	80.3	84.6
2	0.202	0.209	1.39	78.8	83.4
3	0.199	0.207	1.48	79.6	84.5
4	0.201	0.208	1.47	79.5	83.8
5	0.198	0.206	1.48	81.6	85.4
6	0.201	0.208	1.49	79.1	83.9
7	0.199	0.206	1.48	81.4	86.2
8	0.202	0.209	1.46	81.7	86.1
9	0.203	0.210	1.47	80.7	85.4
10	0.201	0.209	1.49	82.3	86.9
11	0.208	0.215	1.48	80.9	85.9
12	0.204	0.211	1.41	79.2	83.6
Average	0.201	0.209	1.47	80.4	85.0

Fiber A-2

	Attenuation at 1550 nm [dB/km]	Attenuation at 1625 nm [dB/km]	λ_c (22 m) [μm]	A_{eff} at 1550 nm [μm^2]	A_{eff} at 1625 nm [μm^2]
1	0.204	0.211	1.51	80.5	84.8
2	0.208	0.215	1.37	79.1	83.4
3	0.203	0.211	1.49	80.2	84.5
4	0.205	0.212	1.46	79.2	83.0
5	0.203	0.211	1.48	80.4	83.9
6	0.205	0.212	1.48	79.8	83.5
7	0.202	0.21	1.48	81.9	86.2
8	0.206	0.214	1.49	80.7	85.3
9	0.206	0.214	1.45	80.5	84.1
10	0.208	0.216	1.48	81.3	85.7
11	0.214	0.222	1.47	80.4	84.9
12	0.209	0.217	1.40	78.3	82.7
Average	0.206	0.214	1.46	80.2	84.3

Fiber B-1

	Attenuation at 1550 nm [dB/km]	Attenuation at 1625 nm [dB/km]	λ_c (22 m) [μm]	A_{eff} at 1550 nm [μm^2]	A_{eff} at 1625 nm [μm^2]
1	0.199	0.207	1.49	80.9	85.5
2	0.197	0.205	1.48	82.1	86.2
3	0.204	0.212	1.50	82.3	86.7
4	0.196	0.204	1.48	80.9	84.7
5	0.200	0.208	1.47	81.1	84.2
6	0.196	0.204	1.48	80.0	84.1
7	0202	0.211	1.46	82.1	85.6
8	0.199	0.207	1.46	79.7	83.3
9	0.199	0.207	1.45	78.9	82.9
10	0.196	0.204	1.47	79.5	83.7
11	0.198	0.206	1.45	80.2	84.6
12	0.196	0.204	1.48	81.3	85.6
Average	0.199	0.207	1.47	80.8	84.8

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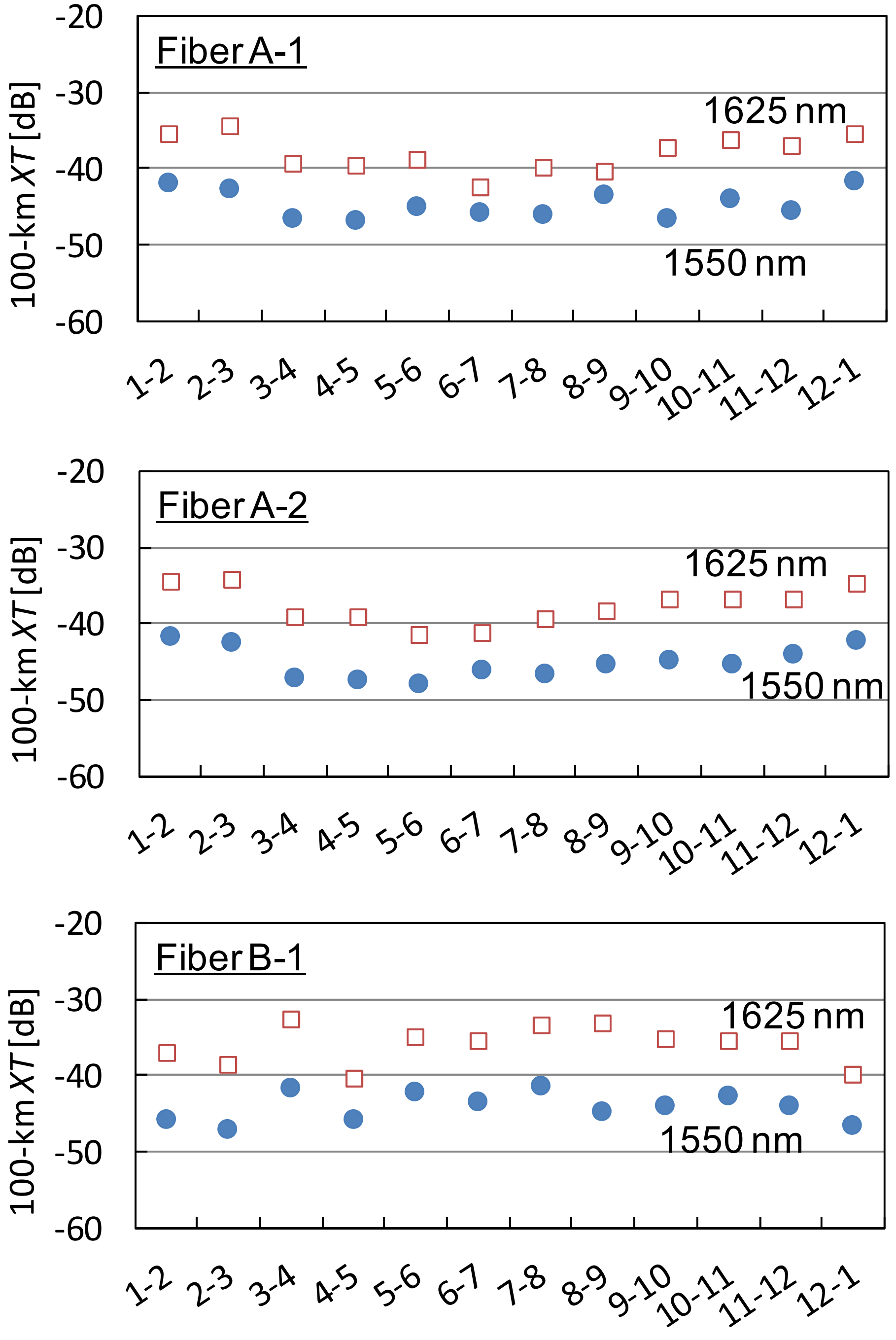

Fig. 7. Estimated 100-km XT from the measured XT of the fabricated fibers.

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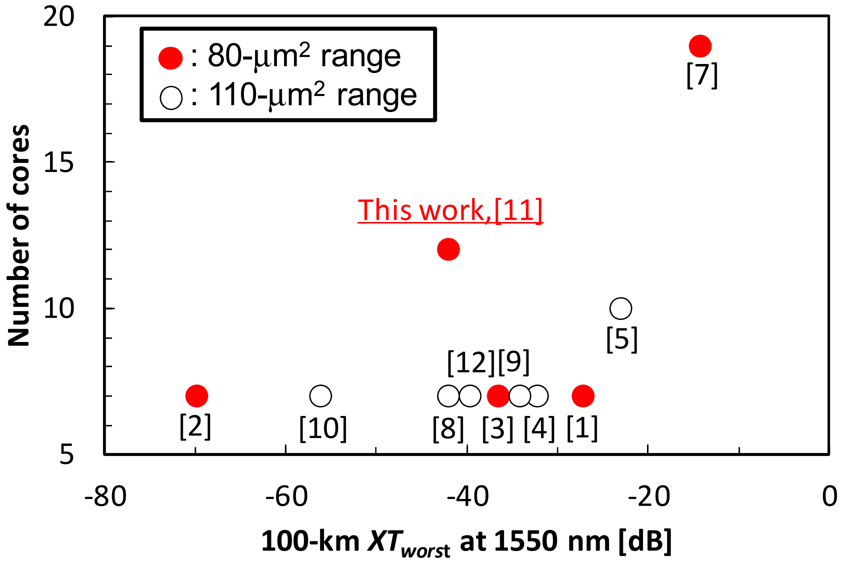

Fig. 8. The relationship between $\mathrm{XT}_{\mathrm{worst}}$ and the number of cores for SM-MCFs.

5. Conclusions

We have proposed a MCF whose cores are arranged on one ring. The characteristics of the proposed structure were theoretically analyzed and experimentally confirmed. The proposed MCF overcame three issues on the MCF with hexagonal close-packed structure. The simulation results indicated that the one-ring structure realizes 12-core fiber with A_{eff} of 80 µm^2 and D_c of 201 µm and 10-core fiber with A_{eff} of 110 µm^2 and D_c of 213 µm. We have fabricated 12-core fibers whose cores were arranged on a hexagon based on the simulation results. The fabricated 12-core fiber realized A_{eff} of 80 µm^2 and 100-km worst crosstalk less than −40 dB at 1550 nm.

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