Large-effective-area ten-core fiber with cladding diameter of about 200 μm

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A multicore fiber with two-pitch layout is proposed to overcome the trade-off between core number and a cladding diameter of a standard hexagonal layout with a single-core pitch. A fabricated ten-core fiber simultaneously realizes effective area of about 120 μm^2 at 1550 nm, small crosstalk, and cladding diameter of 204 μm. The crosstalk between the center core and outer cores is about 30 dB smaller than that between outer cores. The small crosstalk of the center core would help to keep the transmission quality of the center core at the same level as that of the outer cores.

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Multicore fibers (MCFs) are expected to be a next-generation transmission fiber that can overcome the capacity limit of current optical communication systems [1]. Many types of MCF have been developed [2–4] and dense wavelength division multiplexing transmission experiments have been reported [5,6]. Almost all previously reported MCFs took a seven-core structure with equal core pitches for all cores. To improve multiplicity, the number of cores in a MCF is preferred to be larger than seven. However, the number of cores is limited by the cladding diameter in terms of mechanical reliability [7].

In this Letter, we present a ten-core fiber with large effective area (A_{eff}) of about 120 μm^2 at 1550 nm, sufficiently small crosstalk, and a cladding diameter of about 200 μm. A two-pitch core layout is proposed to simultaneously realize these features. After discussion of the design constraints on the standard seven-core structure, the merit of the proposed structure is presented. Finally, the optical characteristics of a fabricated MCF with the proposed structure are presented.

Figure 1 shows schematics of well-known MCFs with seven cores and 19 cores, respectively. All cores in the MCFs are arranged at the same core pitch (Λ). Hereafter, we call the layout a single-pitch layout. The cladding diameter (CD) of a MCF is determined by the Λ and the outer cladding thickness (OCT). Figure 2 shows the relationship between CD and OCT for various Λ. Λ should be larger than a certain value that is determined with target crosstalk and other optical characteristics, such as A_{eff}. OCT has a minimum value to avoid an excess loss increase in the outer cores [4,7,8]. However, CD should be smaller than the diameter at which required reliability is guaranteed.

Our previous work [8] suggested that the minimum value of Λ and OCT is about 40 μm for a trench-assisted MCF with A_{eff} of 110 μm^2 at 1550 nm to suppress crosstalk at less than −30 dB at 100 km and excess loss in the outer cores. In the case of the seven-core structure, CD remains at about 160 μm. However, if we try to employ a 19-core structure, CD reaches to 240 μm, a diameter that has a serious impact on mechanical reliability. Figure 3 shows simulation results of failure probability after 20 years as a function of CD for two bending diameters: $D =$ 30 and 60 mm. The power law theory was used for the simulation [9] and proof level = 1%. The number of bendings = 100 turns. The failure probability of a fiber with 125 μm CD and a 30 mm bending diameter is estimated to be about 10^{-7}. We employed 10^{-7} as a threshold of failure probability because the bending condition is one of the toughest conditions for a conventional optical fiber. If we use MCFs for trunk lines, the failure probability of MCFs should be smaller than 10^{-7} at a bending diameter of 60 mm, which corresponds to the bending diameter in a storage box. The 19-core layout cannot satisfy the threshold at the bending condition. A CD should be smaller than 225 μm to satisfy the limit of failure probability. If we can design a MCF with CD smaller than 200 μm, the failure probability will be about 100 times smaller than that with CD of 240 μm.

We evaluate two types of core layout to assemble as many cores as possible in a cladding with a diameter of less than 225 μm. Figure 4(a) shows a 1-6-6 layout, at which the six outermost cores in a 19-core layout are removed. The structure has been proposed in previous papers, such as [10]. Thirteen cores are assembled in three layers with the same pitch. Figure 4(b) shows a 1-n ($n > 6$) layout with two kinds of pitch. The n is the number of outer cores. The inner pitch Λ_{in} between a center core and outer cores is given by

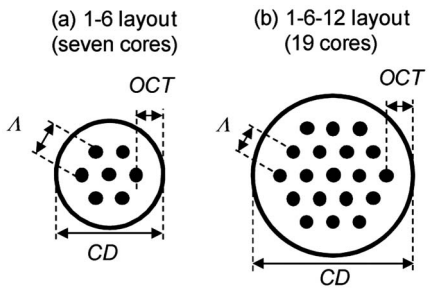

Fig. 1. Schematics of MCFs with single-pitch layouts: (a) seven cores; (b) 19 cores.

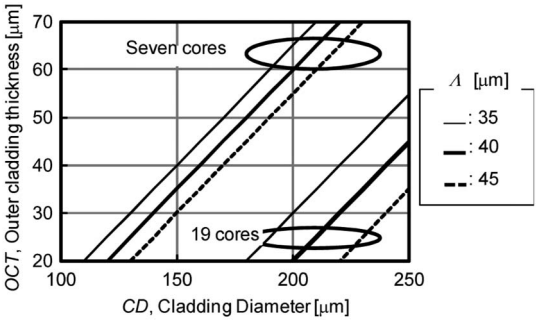

Fig. 2. Relationship between OCT and CD for various core pitches on MCFs shown in Fig. 1.

$$\Lambda_{\text{in}} = \frac{\Lambda_{\text{out}}}{2\sin(\pi/n)}, \tag{1}$$

where Λ_{out} is a pitch between outer cores.

Figure 5 shows the relationship between CD and OCT for various core layouts. $\Lambda = 40\,\mu$m for the single-pitch arrangement. $\Lambda_{\text{out}} = 40\,\mu$m for the two-pitch layout shown in Fig. 4(b). In the case of 40 μm OCT, the CD can be reduced to 225 μm by using a 13-core layout. If we use the two-pitch layout, a ten-core fiber with a cladding diameter smaller than 200 μm can be realized. In the case of 200 μm CD, the number of cores is limited to seven with the case of the single-pitch layout. We can increase the number of cores by 43% thanks to the two-pitch layout.

We have designed and fabricated a large-A_{eff} ten-core fiber. We used the full-vector finite-element method to design a fiber that has A_{eff} larger than 115 μm^2 at 1550 nm and sufficiently small crosstalk [11]. A trench structure was employed to reduce Λ_{out} in terms of crosstalk. Figure 6 shows a cross-sectional view of a fabricated MCF. $\Lambda_{\text{in}} = 59.2\,\mu$m, $\Lambda_{\text{out}} = 40.5\,\mu$m, and OCT $= 43.0\,\mu$m. The cladding diameter of the fabricated fiber was 204.4 μm. The cabled cutoff wavelength of the cores was 1.28 μm. The attenuation at 1550 nm of the cores ranged from 0.22 to 0.24 dB/km. The A_{eff} at 1550 nm of the cores ranged from 116 to 125 μm^2.

Figure 7 summarizes the measured crosstalk at 1550 nm of the fabricated fiber. The same setup as in our previous works [2,3] was used for the measurement. Crosstalk was measured on a 3962 m fiber wound on a spool with a diameter of 210 mm. "2–3" denotes the crosstalk between core 2 and core 3. Figure 7(a) indicates the crosstalk of adjacent outer cores. The measured crosstalk for all outer cores was about −40 dB. The crosstalk at 100 km of the outer cores was estimated to be about −26 dB by using

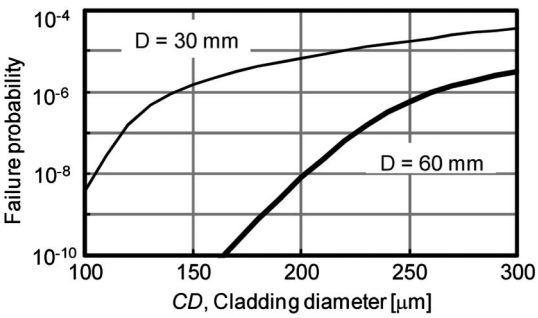

Fig. 3. Failure probability as a function of CD for different bending diameter D.

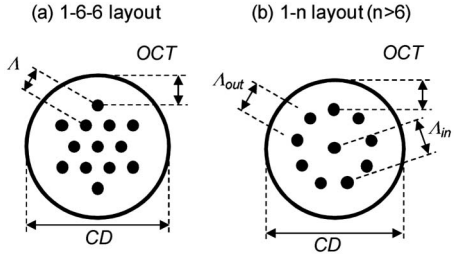

Fig. 4. MCF structure for reducing CD: (a) single pitch; (b) two pitches.

the coupled-power theory [2]. Figure 7(b) indicates that the measured crosstalk between the center core and the outer cores was less than −70 dB, which corresponds to the lower limit of the crosstalk measurement system. The very low crosstalk of the center core compared to the outer cores will be effective to cope with the crosstalk degradation of the center core, assuming all outer cores carry equal signal power [6].

Table 1 summarizes the characteristics of the ten-core fiber presented in this work and the seven-core fiber presented as Fiber C in our previous work [8]. The attenuation of the ten-core fiber was larger than that of the seven-core fiber. The loss deterioration originates not from the two-pitch layout but from the process problem. The attenuation of a ten-core fiber will be the same level as that of a seven-core fiber through manufacturing process adjustment. The 100 km crosstalk of Fiber C was −40 dB, which was smaller than our target value of −30 dB, thanks to a comparatively large core pitch of 43 μm. The 100 km crosstalk of the ten-core fiber was −26 dB, which was slightly larger than the target value, due to a shorter cutoff wavelength and a larger A_{eff} than those of our design target. We can improve the crosstalk of the ten-core fiber to the target value by adjusting the cutoff wavelength and A_{eff} without changing the core pitch or the cladding diameter. The cladding diameter of 204.4 μm is effective

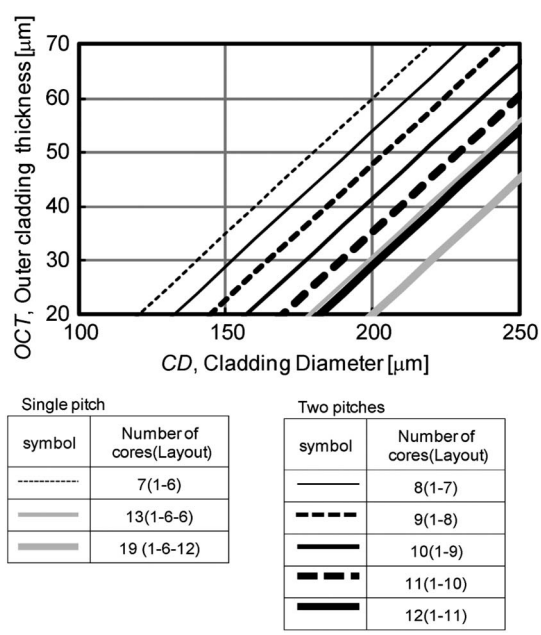

Fig. 5. Relationship between OCT and CD for various structures shown in Figs. 1 and 4.

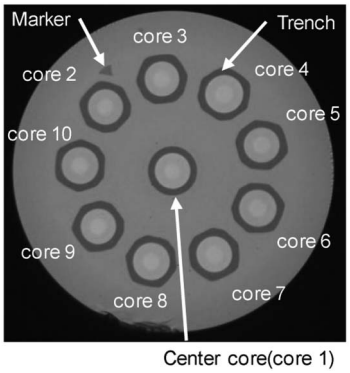

Fig. 6. Cross-sectional view of a fabricated ten-core fiber.

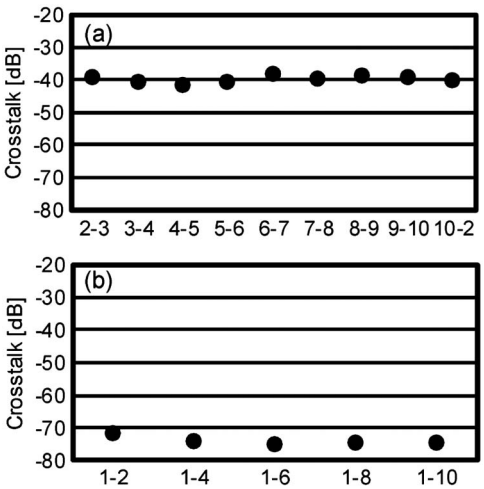

Fig. 7. Measured crosstalk of a 3962 m fiber: (a) crosstalk between outer cores; (b) crosstalk between center core and outer cores.

in suppressing the microbending loss increase, which is an issue for a large effective fiber.

We have proposed a core multiplicity factor (CMF) as a measure of core density of MCFs [8]. The CMF is given by

$$\mathrm{CMF} = \frac{nA_{\mathrm{eff}}}{\pi(\mathrm{CD}/2)^2}, \tag{2}$$

where n is the number of cores with A_{eff} in a cladding, and CD is the cladding diameter.

A relative CMF (RCMF) is a ratio between the CMF of a MCF and a standard single-core single-mode fiber with A_{eff} of $80\,\mu\mathrm{m}^2$ at $1.55\,\mu\mathrm{m}$ and a cladding diameter of $125\,\mu\mathrm{m}$. The maximum RCMF of the seven-core fiber is estimated to be 6.0 with an optimized OCT [8]. The RCMF of the ten-core fiber was 5.4, which was close to the maximum RCMF. The result indicates that the two-pitch layout can efficiently use a limited glass region.

In conclusion, we have proposed a new MCF structure with two core pitches to increase the number of cores with a limited cladding diameter in terms of mechanical reliability. The proposed two-pitch layout realized a large-effective-area ten-core fiber with sufficiently small mechanical reliability for the first time, to the best of our knowledge. The fabricated ten-core fiber simultaneously realized A_{eff} of about $120\,\mu\mathrm{m}^2$ at 1550 nm, sufficiently small crosstalk, and a cladding diameter of $204.4\,\mu\mathrm{m}$. The crosstalk between outer cores was about −40 dB with a 3962 m fiber. The crosstalk between the center core and the outer cores was less than −70 dB with the length. The very small center-core crosstalk will be effective to avoid crosstalk degradation of the center core under the worst case at which all outer cores carry equal power.

Table 1. Comparison with Our Previous Work [8]

Item	Unit	This Work	Previous Work
Core number	—	10	7
Λ	μm	40.5[a]	43.0
OCT	μm	43.0	47.7
CD	μm	204.4	181.3
Primary coating diameter	μm	270.5	249.9
Secondary coating diameter	μm	317.0	301.9
Attenuation at $1.55\,\mu$m[b]	dB/km	0.242	0.198
Cable cutoff wavelength [b]	μm	1.28	1.37
A_{eff} at $1.55\,\mu$m[b]	$\mu\mathrm{m}^2$	116.0	112.4
100 km crosstalk	[dB]	−26[a]	−40
RCMF	—	5.4	4.7

[a]Value between outer cores.
[b]Measured data of a center core.

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