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125-μm-Cladding Coupled 19-Core Fiber with <10-ps/√km Spatial Mode Dispersion and Suppressed Coating Leakage Loss

Ayumi Inoue
Optical Communications Laboratory
Sumitomo Electric Industries, Ltd.
Yokohama, Kanagawa, Japan
inoue-ayumi@sei.co.jp

Takuji Nagashima
Optical Communications Laboratory
Sumitomo Electric Industries, Ltd.
Yokohama, Japan
nagashima-takuji@sei.co.jp

Junya Takano
Optical Communications Laboratory
Sumitomo Electric Industries, Ltd.
Yokohama, Japan
takano-junya@sei.co.jp

Ruben S. Luis
National Institute of Information and Communications Technology (NICT)
Koganei, Tokyo, Japan
rluis@nict.go.jp

Benjamin Puttnam
National Institute of Information and Communications Technology (NICT)
Koganei, Tokyo, Japan
ben@nict.go.jp

Hideaki Furukawa
National Institute of Information and Communications Technology (NICT)
Koganei, Tokyo, Japan
furukawa@nict.go.jp

Tetsuya Hayashi*
Optical Communications Laboratory
Sumitomo Electric Industries, Ltd.
Yokohama, Japan
t-hayashi@sei.co.jp

***Abstract*—We demonstrate a randomly-coupled 19-core fiber with the standard 125-μm cladding, which simultaneously achieves the spatial mode dispersion less than 10 ps/√km and the transmission loss less than 0.20 dB/km, for the first time.**

Keywords—optical fiber, multi-core fiber, coupled multi-core fiber

I. Introduction

Space division multiplexing (SDM) is a promising technology to increase the transmission capacity of optical networks [1], and the multicore fiber (MCF) has been finally commercialized for submarine applications [2], with ultralow-loss uncoupled 2-core fiber [3,4]. For further scaling the spatial channel count in long-haul high-capacity transmission, the randomly-coupled MCF (RC-MCF) is the promising technology [5], which can increase the core density by accepting random mode coupling between cores. Although multiple-input–multiple-output (MIMO) digital signal processing (DSP) is necessary for undoing mode mixing among the cores, the random coupling is beneficial for suppressing the accumulations of spatial mode dispersion (SMD) and mode-dependent loss (MDL). Previous studies have proposed RC-MCFs with 4 cores [6], 7 cores [7], or 12 cores [8], in the standard 125-μm cladding. In OFC 2023, we presented the transmission characteristics (with the brief design and fabrication results) of a newly-developed randomly-coupled 19-core fiber (RC-19CF) [9]. Although the RC-19CF in [9] achieved the record core count in the standard 125-μm cladding whilst achieving the optical properties usable for optical communications, the RC-19CF has a relatively higher loss of 0.215 dB/km at 1550 nm.

In this paper, we demonstrate the 125-μm-cladding RC-19CF simultaneously achieving the SMD less than 10 ps/√km and the transmission loss less than 0.20 dB/km, both for the first time, to the best of our knowledge. In the following, we discuss the design of the RC-19CF, with additional discussions on the effective area design, and on the core pitch design considering the suppression of leakage loss to the coating. The fabrication results are reported after that, which clearly shows the successful suppression of both the SMD and the coating-leakage loss.

II. Design

We designed the randomly-coupled 19-core fiber (RC-19CF) with 19 silica cores in a common 125-μm-diameter cladding. We have studied several core layout including the hexagonal layout, layouts breaking symmetry, and so on, for minimizing the farthest distance between the cores whilst realizing random mode coupling. We found that the optimum layout has the 1 center core, 6 cores on an inner ring, and 12 cores on an outer ring, where every nearest neighboring cores have the same core-to-core distance, as shown in Fig. 1.

The refractive index profile of each core was design with accepting small effective area (A_{eff}) to ensure strong light confinement into the cores. However, we set the lower limit of the A_{eff} at λ = 1550 nm as 60 μm^2 to avoid excessive degradation of optical properties. The A_{eff} of 60 μm^2 is relatively small, but the nonlinear noise suppression thanks to the random coupling [5,7] will realize low nonlinearity and higher tolerance to high input power. The splicing loss would increase with the small mode field diameter of each core, but even with the splice loss increase, the total fiber capacity could be increase with the increase of the channel count [10,11], especially in power-sufficient transmission systems. The cutoff wavelength λ_{cc} for the higher-order modes corresponding to LP11 modes of the cores were designed to be less than 1460 nm to ensure the compatibility to the S+C+L-band transmission. High confinement core design—with small A_{eff} in the range of 60 to 70μm^2 realized by high refractive index contrast between the cores and the cladding—

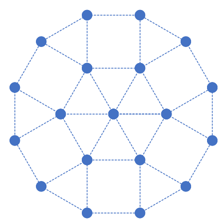

Fig. 1. Optimum core layout for the RC-19CFs, where every pairs of nearest neighboring cores have the same core-to-core distance (the dashed lines in the figure), for enhancing random mode coupling whilst minimizing the farthest distance between cores.

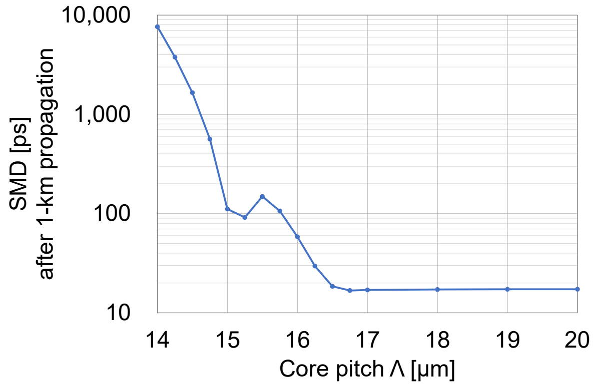

Fig. 2. SMD vs core pitch Λ at 1550 nm of the RC-19CF (replotted from the data in [9]), simulated with the high-confinement cores and the selected optimum core layout.

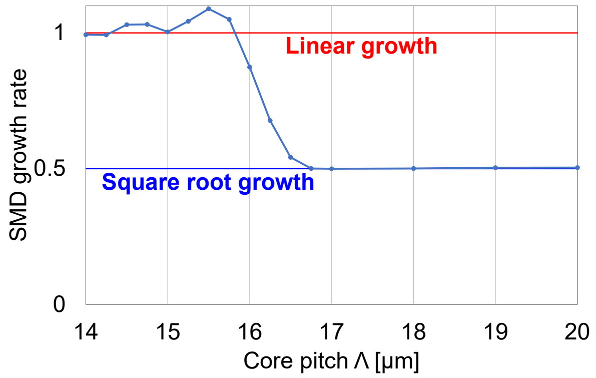

Fig. 3. SMD growth rate of the RC-19CF (replotted from the data in [9]), simulated with the high-confinement cores and the selected optimum core layout.

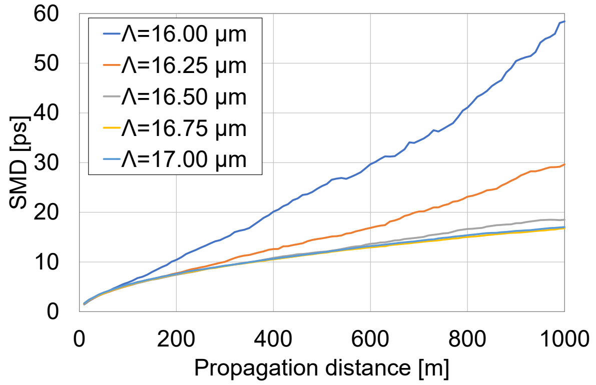

Fig. 4. SMD accumulation during 1000-m propagation for Λ = 16–17 μm. of the RC-19CF (replotted from the data in [9]), simulated with the high-confinement cores and the selected optimum core layout.

is important for realizing both random coupling (low SMD) and low coating-leakage loss.

Figures 2–4 show the numerically investigated relationship between spatial mode dispersion (SMD) and core pitch Λ of the RC-19CF using the simulation method presented in [12,13]. Here, we assumed the fiber bend radius of 0.17 m, the non-random sinusoidal twist with peak rate of 2 turns/m, random twist components with σ of 0.3 turns/√m, and the correlation length of 0.05 m. The SMD after 1-km propagation exponentially decreases with Λ increases from 14 μm to 16.5 μm, and becomes almost constant in the logarithmic scale from Λ = 16.75 μm to 20 μm, as shown in Fig. 2. Figures 3,4 also show Λ around 16.5 μm is the threshold between systematically-coupled regime (shorter Λ, linear SMD growth) and randomly-coupled regime (longer Λ, square-root SMD growth).

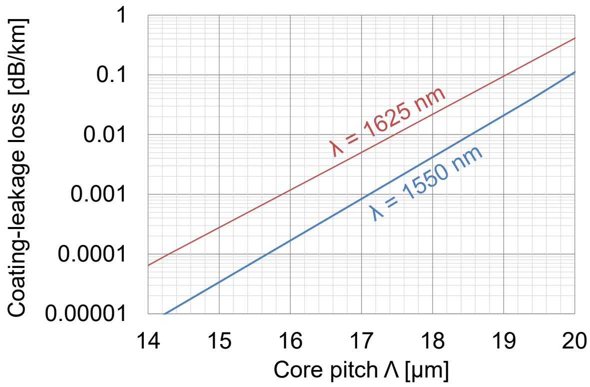

Fig. 5. Coating-leakage loss vs. core pitch Λ, simulated with the high-confinement cores and the selected optimum core layout.

Figures 5 shows the numerically investigated relationship between the coating-leakage loss and core pitch Λ of the RC-19CF. The coating-leakage loss exponentially increases with the decrease of outer cladding thickness OCT (the minimum distance between the outmost core center and cladding-coating interface) [14,15], or the increase of the core pitch as shown in Fig. 5. Therefore, we have to choose the core pitch value such that the SMD and coating-leakage loss can be simultaneously suppressed. To simultaneously ensure the SMD suppression and the leakage loss suppression (≤0.001-dB/km increase) at 1550 nm at least, the core pitch should be designed within the range of 16.5 to 17.1 μm. Therefore, the optimum Λ is considered to be 16.8 μm in this work.

III. Fabrication

Based on the simulation results, we fabricated the RC-19CF from 2 preforms. One is the RC-19CF with the average Λ of 18.0 μm (RC-19CF-1), whose optical characteristics was briefly reported in [9]. The other is RC-19CF with the average Λ of 16.9 μm (RC-19CF-2), which was newly fabricated with improved core pitch control. The cross section of RC-19CF-2 is shown in Fig. 6.

The characteristics of the fabricated RC-19CFs are summarized in Table I, with the target values and the design values. Distinct differences between RC-19CF-1 and RC-19CF-2 are the core pitch Λ and the transmission loss. Unfortunately, RC-19CF-1 has the larger core pitch than its design, and higher transmission loss. This is due to the coating-leakage loss increase due to the decrease of the OCT, as already discussed in Section 2. Figure 7 shows the

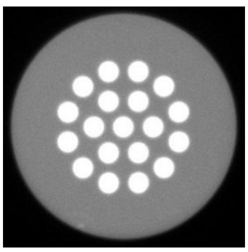

Fig. 6. The cross section of the newly-fabricated RC-19CF with the core pitch of 16.9 μm (RC-19CF-2).

TABLE I. CHARACTERISTICS OF THE RC-19CFS

	Target	Design	RC-19CF-1 [9]	RC-19CF-2 This work
Length [km]	n/a	n/a	63.6	86.1
Λ [μm]	16.5–17.1	16.8	18.0[a]	16.9[a]
A_{eff} [μm][b]	≥60	63	61.8[c]	65.8[d]
λ_{cc} [nm]	≤1460	1360	1363	1375
CD [ps/nm/km][b]	n/a	18.4	17.2	18.2
CD slope [ps/nm^2/km][b]	n/a	0.054	0.055	0.055
Transmission loss [dB/km][b]	≤0.20	n/a	0.215[e]	**0.187[e]**
SMD [ps/√km][b]	n/a	n/a	10.8[f]	**8.7[f]**

a: average values, b: values at 1550 nm, c: calculated from core index profile, d: measured using the incoherent method [16,17], e: measured using OTDR with the center core launch and reception, f: the average of the SMD values of the 19 transmission channels with the center core input and each of 19 core outputs, and the 19 SMD values were measured in 1550 ± 25 nm using the wavelength scanning (fixed analyzer) method [5,18].

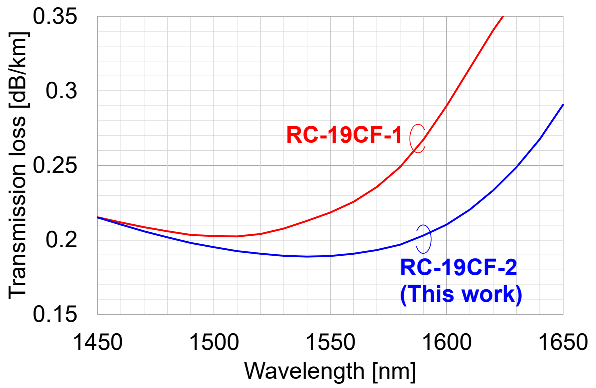

Fig. 7. The transmission loss spectra of the fabricated RC-19CFs, measured using the cut-back method with full-mode reception. The effect of the background noise floor of the measurement setup was numerically eliminated.

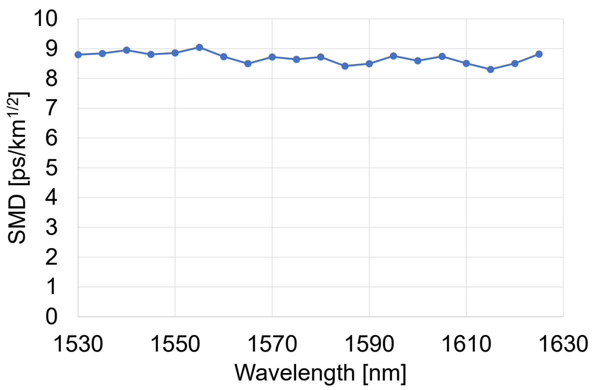

Fig. 8. The wavelength dependence of SMD of RC-19CF-2. The SMD values were caluculated with the same method described in the footnote f of Table I, except that the SMD values were calculated with ±5 nm range. The SMD at 1625 nm was calculated with ±1 nm range, due to a limited wavelength scanning range.

transmission spectra of RC-19CF-1 and RC-19CF-2, which clearly shows the transmission loss increase of RC-19CF-1 in S+C+L band toward longer wavelength. In contrast, thanks to the well-controlled core pitch, RC-19CF-2 has successfully realized the suppressed coating-leakage loss at 1550 nm, and achieved the transmission loss less than 0.20 dB/km at 1550 nm, for the first time among the RC-19CFs. RC-19CF-2 also has a slightly better SMD compared to RC-19CF-1, and achieved the SMD less than 10 ps/√km at 1550 nm, also for the first time among the RC-19CFs. Figure 8 shows the wavelength dependence of the SMD of RC-19CF-2, which demonstrate the SMD less than 10 ps/√km in the whole C+L band.

IV. CONCLUSION

We demonstrated a 125-μm-cladding RC-19CF with the low SMD of 8.7 ps/√km and the low transmission loss of 0.187 dB/km. Both the achieved SMD and transmission loss set the record as RC-19CFs. In addition, we realized the 125-μm-cladding RC-19CF with suppressed coating-leakage loss, for the first time, thanks to the improved precise core pitch control. The present results demonstrate the future scalability of spatial channel count of the RC-MCFs.

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