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A 125-μm Cladding Diameter Uncoupled 3-mode 4-core Fibre with the Highest Core Multiplicity Factor

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Abstract *The highest relative core multiplicity factor of beyond 12 is achieved in a 125-μm cladding diameter uncoupled multi-core fibre by using a common depressed layer design. Feasible inter-core crosstalk below -40 dB/km and effective area over 80 μm² in C-L band are successfully obtained simultaneously. ©2022 The Author(s)*

Introduction

A few-mode multi-core fibre (FM-MCF) is beneficial for maximizing a spatial channel density [1] and achieving a large transmission capacity of over 10 Pb/s/fibre [2]. An MCF with a standard cladding diameter [3–8] would be a key factor because a larger cladding diameter severely degrades the mass productivity. It is necessary for maximizing spatial channel density to optimize the refractive index profile and inter-core pitch considering the trade-off relationship among inter-core crosstalk (XT), mode-field diameter (MFD) and confinement loss α_c. FM-MCFs with a standard cladding diameter have been fabricated in Refs. [9] and [10]. Regarding Ref. [10], although the 3-mode 4-core fibre (3M-4CF) enabled transmission of 12 spatial modes and a low XT below -50 dB/km by adopting air-holes between neighbouring cores, MFD was smaller than conventional single-mode fibres (SMFs). Thus, a relative core multiplicity factor (RCMF) [11] of more than 10 has not yet been achieved in a standard cladding diameter FM-MCF.

In this paper, we propose a 125-μm cladding diameter 3M-4CF with a common depressed layer, which is associated with the W-shaped index profile. Then, we confirmed that a fabricated fibre with a cladding diameter of 125 μm achieved an XT of LP_{11} below -40 dB/km at a wavelength of 1625 nm and A_{eff} over 80 μm² simultaneously. Our proposed design enables the highest RCMF of more than 12 among standard cladding uncoupled MCFs while keeping the feasible XT.

3M-4CF with a common depressed layer

Figure 1 illustrates a cross-sectional image and corresponding refractive index profile on a blue broken line which we considered in this paper. A cladding diameter is set to be 125 μm. The number of cores is four and each core supports to propagate three modes: (a) contains four step index (SI) cores, (b) consists of four individual W-shaped cores (IW) and (c) has a common depressed layer (CD). The core radius and inter-core pitch are represented by a and Λ, respectively, and the relative refractive index difference Δ_c is given by $\Delta_c = (n_{core}^2 - n_{clad}^2)/2n_{core}^2$, where n_{core} and n_{clad} are refractive indices of the core and the clad, respectively. In this paper, n_{core} is assumed to be pure silica glass. Regarding the IW and CD, the widths of the depressed layer are represented by w, and the relative refractive index difference Δ_d is given by $\Delta_c = (n_{dep}^2 - n_{clad}^2)/2n_{clad}^2$ using a refractive index of the depressed layer n_{dep}. In this study, we set w/a = 3 and Δ_d/Δ_c = 0.3 in accordance with the design example of a cut-off shifted fibre reported in Ref. [12]. We assumed a cut-off wavelength λ_c for LP_{21} and MFD at 1550 nm for LP_{01} mode to be 1530 nm and 10.0 μm, respectively. We also set requirements on α_c and inter-core XT between two neighbouring cores less than 0.01 dB/km and -47dB/km by which a 100-km long 16-quadrature-amplitude-modulation transmission is achieved with an optical signal-to-noise ratio (OSNR) penalty less than 1 dB [13]. Regarding the IW, the

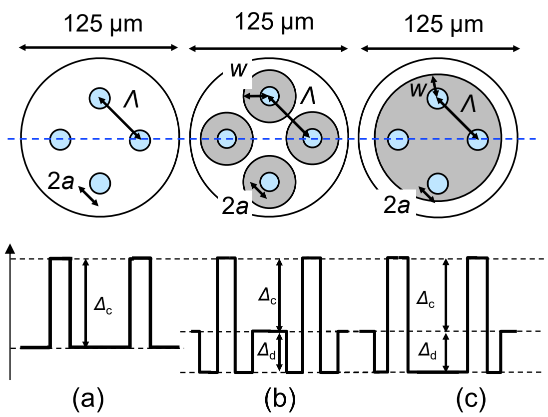

Fig. 1 Cross-section image and refractive index profile on blue broken line. (a) SI cores, (b) individual W-shaped cores (IW) and (c) common depressed layer (CD).

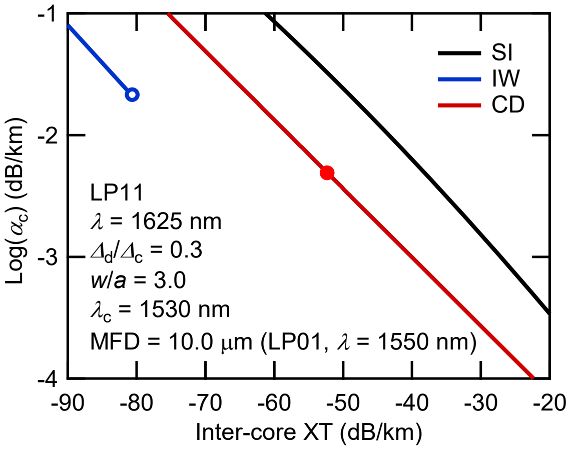

Fig. 2 Calculated α_c and inter-core XT of LP_{11} mode. Black, blue and red correspond to SI, IW, and CD types, respectively.

edges of the depressed layers tend to be close with each other because of the large core radius. Therefore, we assumed as Λ - 2w > 10 μm to avoid fabrication difficulties.

Figure 2 shows the calculated relationship between α_c and the inter-core XT of LP_{11} at a wavelength of 1625 nm. The black, blue and red lines represent the results for the SI, IW and CD, respectively. The open circle indicates the IW of Λ - 2w = 10 μm. It can be seen from Fig. 2 that the SI has the most stringent trade-off among the discussion models, and an achievable α_c was found to be larger than 0.02 dB/km at an XT of -47 dB/km. Although IW can reduce the XT effectively, it cannot reduce the α_c sufficiently because of the structural interference between neighbouring cores. Figure 2 also reveals that CD enables to satisfy the requirements for α_c and the inter-core XT simultaneously. Moreover, a α_c less than 0.001 dB/km is also achievable for a sufficiently low XT. We then fabricated a CD type 3M-4CF shown by a filled circle in Fig. 2, at which the designed a, Δ_c and Λ are 6.1 μm, 0.58% and 41.0 μm, respectively.

Experiments

Figure 3 shows a cross-sectional image of a fabricated CD type 3M-4CF with pure silica glass cores and a fluorine-doped common depressed layer. The cladding diameter was 125 μm. The structural parameters of a = 6.0 μm, Λ = 41.3 μm, w/a = 2.7 and Δ_d/Δ_c = 0.33 were almost comparable with the designed values. However, a Δ_c of 0.48% was smaller than the designed value and resulted in the larger Δ_d/Δ_c.

Table 2 summarizes the targeted and fabricated optical properties of the fabricated CD type 3M-4CF. Each LP mode was excited by the offset splice of mode MUX/DEMUX to a core under test, and a mode extinction ratio of less

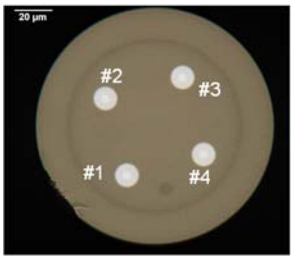

Fig. 3 Cross-section of the fabricated CD type 3M-4CF.

Table 2 Measured optical properties of the fabricated CD type 3M-4CF.

	λ (nm)	Target	#1	#2	#3	#4
MFD^{01} (μm)	1550	10.0	10.3	10.3	10.3	10.2
A_{eff}^{01} (μm^2)	1550	-	87.8	83.3	82.8	82.1
λ_c^{21} (nm)	-	<1530	1353	1353	1351	1354
α_{01} (dB/km)	1550	-	0.19	0.21	0.18	0.19
	1625	-	0.20	0.22	0.22	0.21
α^{11} (dB/km)	1550	-	0.31	0.27	0.27	0.29
	1625	-	1.15	0.68	0.64	1.36
α_b^{11} (R = 30 mm, dB/100 turns)	1625	< 0.1	0.2	0.1	0.2	0.2

than 18 dB was confirmed. The MFD and effective area A_{eff} of LP_{01} at a wavelength of 1550 nm were 10.2–10.3 μm, and 82.1–87.8 μm^2, respectively. The λ_c measured in the 22 m-long sample (or cable cut-off wavelength) for LP_{21} found in 1351–1354 nm was shorter than the designed values, and it was considered as the effect of the smaller Δ_c. The transmission loss of LP_{01} mode α_{01} of 0.18–0.21 dB/km and 0.20–0.22 dB/km at wavelengths of 1550 nm and 1625 nm was comparable to the conventional single-mode fibre, respectively. However, the loss of LP_{11} modes α^{11} at 1550 nm and 1625 nm of 0.27–0.31 dB/km and 0.64–1.36 dB/km noticeably degraded. It can be considered as the effect of an insufficient effective refractive index difference Δn_{eff} between the LP_{11} modes and leaky mode group. Although Ref. [14] recommends a Δn_{eff} larger than 0.0032 to suppress the micro-bending loss sufficiently, the Δn_{eff} of our fabricated CD type 3M-4CF was calculated as 0.0011 by the finite-element method analysis. Therefore, the observed large losses of LP_{11} modes is supposed to be caused by the micro-bending of the tested fibre. We should note that our CD type 3M-4CF needs further optimisation of Δn_{eff} to support L-band operation. The bending loss of LP_{11} α_b^{11} with a bending radius R of 30 mm at a wavelength of 1625 nm was estimated by the measured attenuations caused by a single turn. It was also found that α_b^{11} was slightly larger than the design target. We also confirmed a differential modal delay between the LP_{01} and LP_{11} modes at a

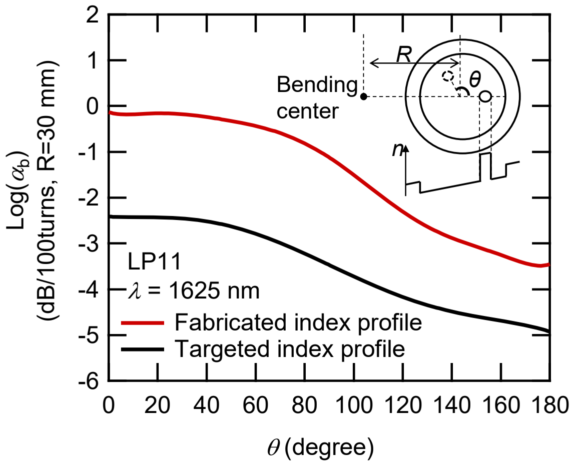

Fig. 4 Calculated α_b^{11} as a function of core position angle against the bending radial axis θ.

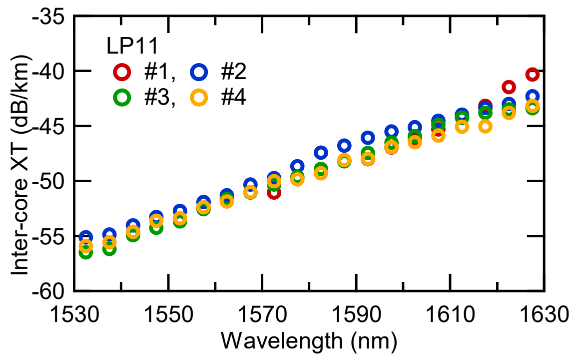

Fig. 5 Measured inter-core XT of LP11 mode.

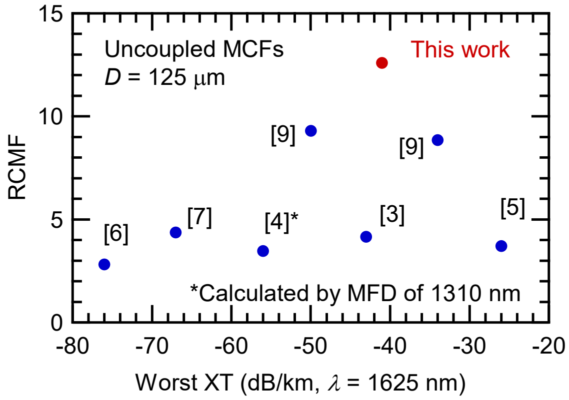

Fig. 6 Reported XT and RCMF of uncoupled MCFs with a 125-μm cladding diameter.

wavelength of 1550 nm of 3.9 ns/km or less, which was measured by the time-of-flight measurement of a 50-ps optical pulse.

α_b of the CD type MCF depends on core location and bending direction because of the anisotropy of the depressed and cladding structure [15]. Figure 4 shows the calculated α_b^{11} as a function of θ, which is defined as the angle of the core position from the bending radial axis as shown by the insert figure. Black and red lines represent the α_b calculated in assuming the targeted and fabricated refractive index profiles, respectively. It can be seen from Fig. 4 that α_b is altered along with θ, and the averaged value was obtained as 0.2 dB/100turns for the fabricated refractive index profile. Figure 4 reveals that a 0.09% decrease in Δ_c degrades α_b about two digits, and the measured value of 0.1–0.2 dB/100turns agrees well with the calculated estimation. Furthermore, Fig. 4 shows that α_b varies by two orders of magnitude depending on θ. Thus, this needs to be taken into account in further optimisation of the CD type 3M-4CF.

Figure 5 shows the inter-core XT spectrum of the LP_{11} mode measured on the fabricated 3M-4CF winding 75-mm radius spool. Red, blue, green and yellow symbols were obtained in core 1, 2, 3 and 4, respectively. Each symbol indicates the averaged value in a wavelength range of ±2.5 nm. We confirmed inter-core XTs in a range of -43 to -40 dB/km at a wavelength of 1625 nm. Although these slightly exceeded our target value, the fabricated fibre seems to support 100-km class transmissions of the quadrature phase shift keying format in the C-L band while maintaining the OSNR penalty due to the XT noise less than 1 dB [13]. These observed XTs seemed to be affected by Δ_c decrease of the fabricated fibre. Thus, the requirement of the XT is expected to be satisfied by achieving the optimized Δ_c.

Figure 6 summarizes the relationship between RCMF and XT at 1625 nm among the reported uncoupled type MCFs operating in the C-L band with a 125-μm cladding diameter. Here, to compare RCMFs between single-mode MCFs and FM-MCFs simultaneously, we calculated them by considering the A_{eff} of LP_{01} at a wavelength of 1550 nm as that of LP_{11} in accordance with Ref. [16]. We should note that the RCMF of Ref. [4] was calculated by the estimated A_{eff} by the reported MFD at a wavelength of 1310 nm. Figure 6 confirms that the CD type 3M-4CF successfully achieved an RCMF of more than 10 in the standard 125-μm cladding diameter for the first time while keeping an XT of less than -40 dB/km. These results show that the proposed CD layer structure is beneficial for achieving the effective use of core and mode multiplexing in a limited cladding diameter.

Conclusion

We achieved an RCMF of more than 10 for the first time among MCFs with a 125-μm cladding diameter while keeping the feasible XT and A_{eff} values by using a CD layer structure. Although the micro-bending loss property needs further optimisation, our proposed design concept is beneficial for achieving a 125-μm cladding diameter MCF with higher spatial multiplicity.

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