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High-count Multi-Core Fibers for Space-Division Multiplexing with Propagation-Direction Interleaving

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Abstract: By introducing a square lattice structure for bidirectional core assignments in multi-core fibers, the effectiveness of propagation-direction interleaving for crosstalk reduction can be increased, realizing a 24-core fiber with -30.6 dB crosstalk over 100 km.

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1. Introduction

Uncoupled single-mode multi-core fibers (MCFs) have been widely used in the transmission experiments with capacities well beyond those achieved by single-mode fibers, due to their high spatial utilization efficiency.

The state-of-the-art one Pbit/s MCF transmission over 52 km [1] used a homogeneous trench-assisted 12-core fiber with one-ring structure (ORS) for inter-core crosstalk (XT) reduction. Propagation-direction interleaving (PDI) has been proposed to further increase the transmission distance by reducing the XT [2, 3], where a 12-core fiber with dual-ring structure (DRS) was used. So far, all the works on the bidirectional core assignments under PDI have been done based on core arrangement structures such as hexagonal close-packed structure (HCPS), ORS or DRS [4, 5].

In this paper, we theoretically evaluate the XT reduction effects of PDI in homogenous trench-assisted MCFs with different core arrangement structures. We show that the effectiveness of PDI can be increased significantly by adopting a new core arrangement structure, i.e. square lattice structure (SLS). We also show that by adopting PDI, a square lattice arranged 24-core fiber with the worst XT of -30.6 dB at 1620 nm over 100 km can be achieved, enabling MCF transmissions with higher spatial utilization efficiency, hence more capacity.

2. Formulation for Co-directional and Contra-directional XT

For unidirectional propagation, the mean XT between 2 adjacent cores in homogeneous trench-assisted MCFs, XT_{μ}'' , can be simplified to the following expression [6], by relating to the mean XT in homogeneous normal step-index MCFs

$$XT_{\mu}'' = XT_{\mu}' \Gamma \exp\left[-4(W_2 - W_1) \frac{w_{tr}}{a_1}\right], \quad (1)$$

where XT_{μ}' is the mean XT in normal step-index MCFs. $\Gamma = W_1/[W_1 + (W_2 - W_1)w_{tr}/\Lambda]$, in which $W_1 \approx 1.1428V_1 - 0.996$ for $1.5 \leq V_1 \leq 2.5$ [7], where V_1 is the V number which determines the modes propagating in a fiber. $W_2 = (V_2^2 + W_1^2)^{1/2}$, in which $V_2 = ka_1n_0\sqrt{2}[\Delta_2]$, where $k = 2\pi/\lambda$ is the wave number and λ is the wavelength of light in vacuum, a_1 , n_0 and Δ_2 are the core radius, refractive index of cladding and relative refractive index difference between trench and cladding. w_{tr} and Λ are the trench width and core pitch, respectively.

For the case of PDI, the XT difference in dB between the backward propagated (or contra-directional) XT ($XT_{b,dB}$) and forward propagated (or co-directional) XT ($XT_{f,dB}$) between two adjacent cores in MCFs is expressed as

$$XT_{b,dB} - XT_{f,dB} = 10 \log\left(\frac{XT_b}{XT_f}\right) = 10 \log\left\{\frac{S\alpha_R}{2\alpha} \left[\frac{\exp(\alpha L) - \exp(-\alpha L)}{\alpha L} - 2 \exp(-\alpha L)\right]\right\}, \quad (2)$$

using Eqs. (1), (3) and (5) in [5], where XT_b and XT_f are the backward propagated XT and forward propagated XT, respectively. S and α_R are the recapture factor of the Rayleigh scattering component into the backward direction and the attenuation coefficient due to Rayleigh scattering, respectively. α and L are the fiber attenuation coefficient in linear scale and fiber length, respectively. As can be seen from Eq. (2), the XT difference does not depend on the core pitch Λ (or in other means, mode coupling coefficient). For a fiber length of 100 km, XT_b is around 18.6 dB lower than XT_f and thus, if this property can be used in an effective manner, a significant XT reduction can be achieved in PDI.

3. Previous High-count Core Arrangement Structures for PDI

In our previous work [4], the effects of PDI in both HCPS 18-core and ORS 12-core are investigated, as shown in Figs. 1(a) and 1(b), where the center core is added to 18-core and the propagation direction in the cores with “x” is opposite to that in the cores without the mark. In addition, DRS has also been proposed for XT reduction under PDI, and 12-core fiber with DRS was used in capacity-distance product record transmission [3], where the cores are assigned as shown in Fig. 1(c). For HCPS and DRS under PDI, the number of adjacent cores with the same propagation direction, N_{adj} , can not be reduced to zero, as the forward propagated XT is much higher than the backward propagated XT arising from the Rayleigh backward scattering, the worst XT is determined by forward propagated XT from the N_{adj} adjacent cores. The XT improvement is determined by the reduction of N_{adj} by PDI compared to unidirectional propagation. For ORS, on the contrary, N_{adj} can be reduced to zero using the core assignment as shown in Fig. 1(b), thus, the XT is determined by the backward propagated XT in the two adjacent cores and the forward propagated XT in the two non-adjacent cores at a distance of 2Λ or $\sqrt{3}\Lambda$, the later one is much lower due to the enlarged core-to-core distance between cores with the same propagation direction. The XT improvements between unidirectional and PDI cases, ΔXT , for these different core arrangement structures are thus calculated and listed in Table 1, where the worst XT scenario (cores with the maximum number of adjacent cores under the same propagation direction) is considered, where “Uni” denotes unidirectional propagation. The ΔXT for ORS is based on MCFs of 100 km, which is around 18.6 dB as described above. It should be noted that ΔXT does not depend on the core pitch nor cladding diameter as it is a relative value, while the absolute XT depends on the core pitch.

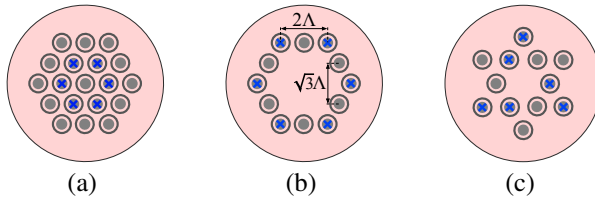


Fig. 1: Bidirectional core assignments in (a) 19-core HCPS, (b) 12-core ORS and (c) 12-core DRS.

Table 1: XT improvement (ΔXT) by PDI in core arrangement structures

Structure names	N_{adj}		ΔXT (dB)
	Uni	PDI	
HCPS	6	2	4.77
ORS	2	0	18.6
DRS	4	1	6

4. New Core Arrangement Structure for PDI

In order to increase the effectiveness of PDI for XT reduction, a new core arrangement structure, i.e. SLS, can be used, as shown in Fig. 2, where both 12-core and 24-core MCFs are shown. The structural parameters are the same as in Table 2 from Ref. [6], where $\Delta_2 = -70\%$ is used in this work, with corresponding effective area, A_{eff} , of $78 \mu m^2$ at 1550 nm. The cladding diameter and cladding thickness are assumed to $230 \mu m$ and $30 \mu m$, resulting in a core pitch of $53.8 \mu m$ and $33.3 \mu m$ for SLS 12-core and SLS 24-core MCFs, respectively. Under the same cladding diameter and cladding thickness, the core pitches for ORS and DRS are $42.5 \mu m$ and $49.1 \mu m$, respectively.

As can be seen from the figures, the cores with the same propagation direction are assigned diagonally, thus the total number of cores in each direction are the same. For any core in SLS, there are no adjacent cores with the same propagation direction at a distance of Λ . For the cores with the worst XT scenario, there are 3 or 4 cores (3 for 12-core and 4 for 24-core cases) with the same propagation direction at a distance of $\sqrt{2}\Lambda$ and 4 cores with the opposite propagation direction at a distance of Λ . The forward propagated XT from cores at a distance of $\sqrt{2}\Lambda$ is much lower than the backward propagated XT from cores at a distance of Λ , as the XT reduction due to enlarged core-to-core distance from Λ to $\sqrt{2}\Lambda$ is much significant than 18.6 dB. By only considering the backward propagated XT from cores at a distance of Λ , the worst XT as a function of wavelength for 12-core (ORS, DRS and SLS) and SLS 24-core fibers can then be directly plotted based on Eqs. (1) and (2), as shown in Figs. 3(a) and 3(b), respectively.

As can be seen from Fig. 3(a), the worst XT for unidirectional propagation in SLS is the lowest among ORS, DRS and SLS, due to the enlarged core pitch in the new core arrangement structure. The worst XT in 12-core fiber with SLS can be reduced by around 27 dB at 1550 nm compared to that in 12-core fiber with DRS over a fiber length of 100 km without PDI. Thus, SLS is superior to ORS and DRS in terms of XT even for unidirectional propagation.

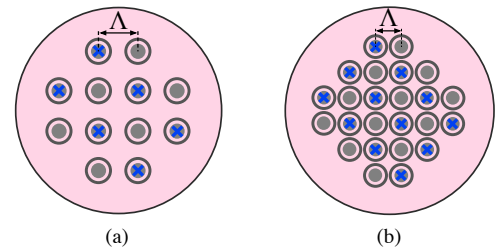


Fig. 2: Bidirectional core assignments in (a) 12-core SLS and (b) 24-core SLS.

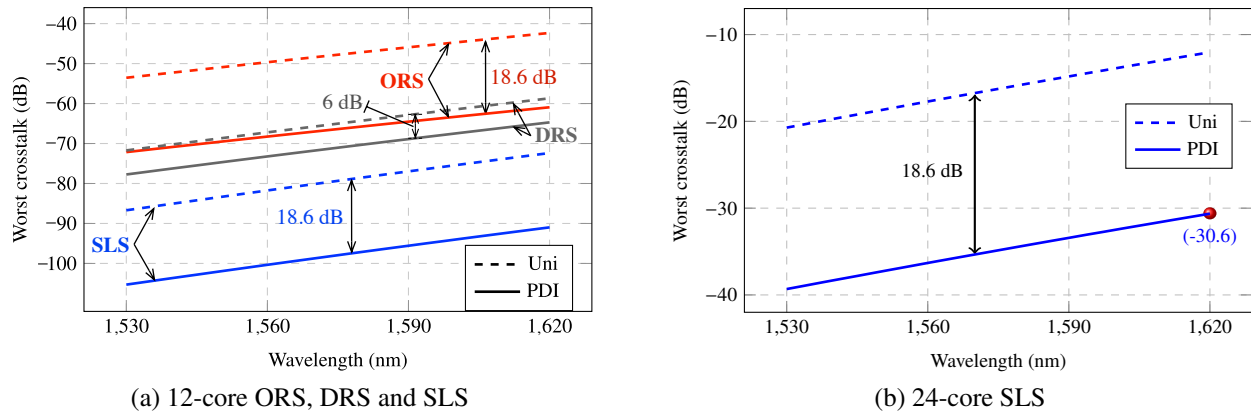


Fig. 3: Worst XT over 100 km as a function of wavelength for (a) 12-core fiber and (b) 24-core fiber under different schemes, with bending radius of 140 mm.

As described above, the adoption of PDI in ORS and DRS as shown in Figs.1(b) and 1(c) results in 18.6 dB and 6 dB XT improvement compared to unidirectional propagation, as illustrated in Fig. 3(a). The effectiveness of PDI can be increased significantly and maximized by using ORS or SLS. Compared to DRS and SLS, the core pitch in ORS is much smaller under the same cladding diameter and cladding thickness, thus, the worst XT in ORS under PDI is the highest, even though the XT reduction amount by PDI in ORS is much larger than that in DRS. For the 24-core fiber, the worst XT is around -12 dB at 1620 nm over 100 km without using PDI. Due to the wavelength-dependent property of XT in MCFs [8], the XT at the longest wavelength in the whole transmission band determines the over-all transmission performance. As shown in Fig. 3(b), the worst XT is reduced by 18.6 dB by adopting PDI, reaching a XT of -30.6 dB at 1620 nm over 100 km, which is sufficiently low to adopt 32QAM in C + L bands, enabling MCF transmissions with a potential total capacity as high as 2 Pbit/s. The XT reduction amount by PDI in SLS is limited by Rayleigh scattering, thus, any technique that weakens this physical effect will further reduce the XT.

5. Conclusion

We have investigated theoretically the XT reduction effects in different core arrangement structures such as HCPS, ORS and DRS for PDI and proposed a new core arrangement structure, i.e. SLS, for effective space-division multiplexing with PDI in MCF transmissions. It is worthwhile to note that by using SLS instead of ORS or DRS for 12-core fiber, the core pitch can be enlarged, resulting in much lower XT for unidirectional propagation. By adopting PDI in SLS, the worst XT in 12-core and 24-core MCFs of 100 km can be reduced by as much as 18.6 dB, which is only limited by Rayleigh scattering, compared to the XT reduction of 4.77 dB and 6 dB by PDI in HCPS and DRS, respectively. A square lattice structured 24-core fiber with a XT of -30.6 dB at 1620 nm over 100 km can be achieved by adopting PDI with diagonal core assignment, enabling MCF transmissions with higher spatial utilization efficiency.

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