On the limits of multimode SDM transmission capacity

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***Abstract*— We review our recent work on the optimization of multimode fibers to support over 1000 spatial modes, focusing on minimizing differential mode delay and maximizing throughput. We identify a practical mode scaling limit due to Rayleigh scattering, macro-bend loss and coating loss.**

***Keywords*— multimode fibers, space-division multiplexing, high-capacity transmission**

I. Introduction

Space-division multiplexing (SDM) has emerged as a solution to overcome the capacity limit of single-mode fibers (SMFs) [1]. Increasingly more advanced SDM schemes have been proposed, from bundles of SMFs and uncoupled core multi-core fibers (MMFs) to coupled-core multi-core fibers (CC-MCFs) and multimode fibers (MMFs). Besides the immediate gains in trunk and connectivity density, the potential opto-electronic integration gains at the transceiver are critical to the overall SDM proposition. Namely, spatial super-channels can share one laser for N spatial tributaries and thus share common digital signal processing (DSP) functions such as laser frequency/phase recovery [2]. The larger the spatial density, the larger the potential integration gains. Also, with all crosstalk spatial paths originating and terminating at the same transceiver, crosstalk can be cancelled using as multiple-input multiple-output (MIMO)-DSP [3] – to address crosstalk from fibers and transceivers.

Among the possible SDM approaches, bundles of SMFs and uncoupled core MCFs were the first adopted given their compatibility with existing network elements (e.g., transceivers and amplifiers) [4]. However, their potential for integration gains is limited – even for CC-MCFs, the optimal number of cores is likely to be $\lesssim$20 [5]. Instead, we have recently explored the potential of multimode fibers (MMFs) for much larger spatial information density. Here we review what are the practical limits to the number of modes MMFs with larger core and index contrast than conventional.

Yet, the benefits provided by multimode SDM come with significant challenges, namely group delay (GD) spread [3] – given the interplay between differential mode delay (DMD) and linear mode coupling (LMC) – and mode-dependent loss (MDL) [6]. While GD spread can be addressed using MIMO-DSP [7] – with the complexity scaling with delay spread, MDL imposes a fundamental loss of throughput. To counteract GD spread, and minimize MIMO-DSP complexity, multimode SDM fibers are designed with a graded-index core, assisted with a cladding trench [8] to ease the macro-bend loss (MBL) affecting higher-order modes. However, accommodating an increased number of modes necessitates tolerating larger DMD and MDL, as discussed in the following.

II. Linear Impairments in Optimized Multimode Fiber

In this work, we consider a refractive-index profile composed by a graded-index core and a cladding trench, to reduce GD spread and MBL, with 6 parameters for optimization: the core grading exponent, α, the refractive index relative difference at the core and trench, Δn_{co} and Δn_{tr}, respectively, the core radius, w_1, the trench to the core distance, w_2, and the trench width, w_3. In [9], we shown that optimization can be simplified to an exhaustive search over (Δn_{co}, w_2, w_3) and an iterative search over (α, Δn_{tr}), by noting that the latter forms a convex space and by using the largest w_1 for a given Δn_{co} that allows for a given target number of modes.

Given that MIMO-DSP complexity scales with the total delay spread, we primarily optimize fibers to minimize DMD. Noting that each mode pair has its own *DMD* value, here we consider the maximum DMD over all pairs and over the whole C-band, taking the fundamental mode as reference – we dub this quantity as *maxDMD*. Fig. 1 shows *maxDMD* as a function of the number of guided spatial modes for several Δn_{co} values. Full lines shown the optimization search result and the dashed lines correspond to analytical approximations derived in [9] – the latter approximate α and Δn_{tr}, for large number of modes ($\gtrsim$100), as:

$$\alpha^{\text{(quasi-opt)}}(\Delta n_{co}) \approx 2\cdot(\ 1 - 0.85\cdot\Delta n_{co}\ ) \qquad (1)$$

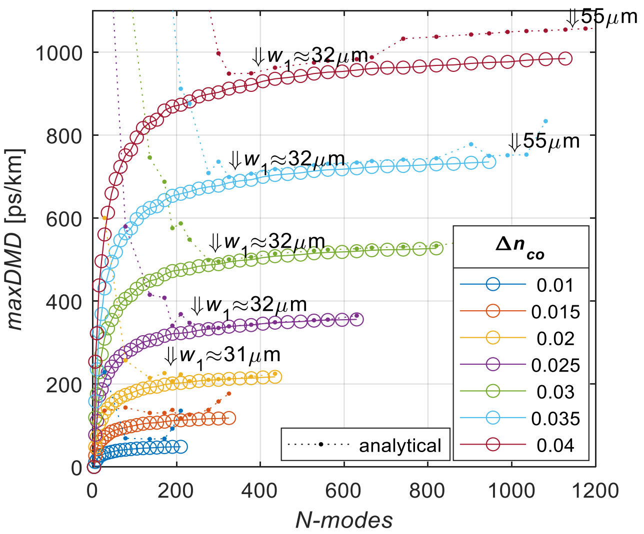
$$\Delta n_{tr}^{\text{(quasi-opt)}}(w_1, \Delta n_{co}) \approx -0.3\cdot(75/w_1[\mu\text{m}])^2\cdot\Delta n_{co} \qquad (2)$$

From Fig.1, it can be seen (from the full lines) that larger Δn_{co} allows supporting an increasingly larger number of modes (bounded by a 125µm cladding) at the cost of a higher *maxDMD*. But critically, *maxDMD* is found to scale quickly before levelling out as the radius of the core becomes larger than 30 µm – similar observation in [10] for $\Delta n_{co} \approx 0.01$. Therefore, at least *maxDMD*-wise, and for a given number of target modes, one should use the combination with the largest w_1 and lowest Δn_{co} that allows for the number of modes being targetted. Also from Fig. 1, one can note that over 435 spatial modes and 630 spatial modes can be supported with <250 ps/km and <450 ps/km, respectively – 250 ps/km is typical of conventional OM fibres at 850 nm and 450 ps/km relates with the 55 spatial modes used for 1.5 Petabit/s experimental transmission in [11]. Note that manufacturing tolerances are neglected here, for such an analysis see [9].

The scaling in *maxDMD*, and N-modes, with w_1 and Δn_{co} are followed by a scaling in Rayleigh scattering loss, MBL, and coating loss, as shown in [9]. Rayleigh scattering has been found to scale mostly with Δn_{co} – given the associated Ge-doping increase, approaching 0.1 dB/km for $\Delta n_{co} = 0.03$. On the other hand, the MBL penalty tends to increase with N-modes (for a given Δn_{co}) reaching levels well beyond that of SMFs for $w_1 > 50$ µm. Finally, we verified that allowing for larger cores than in conventional fibers (i.e., radius = 25µm) can make the coating loss of the fiber increase [12] – as the evanescent field of higher order modes reaches the cladding-coating boundary leading to excess loss. The excess losses are found critical as the profile outer dimensions approach the cladding diameter, 125 µm.

III. Coupled Transmission and Channel Throughput

In this section, we estimate the achievable throughput for the optimized fibers in Section II considering all the main linear



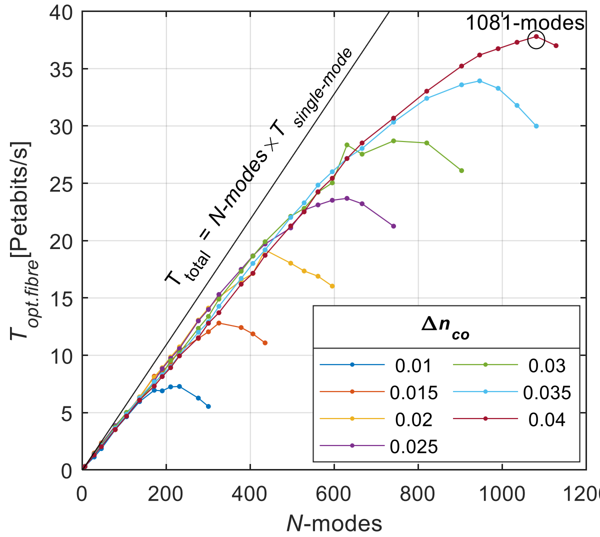


Fig. 1. *maxDMD* [ps/km] optimum values as a function of the number of spatial modes for different Δn_{co} values: for optimization search 'o'-markers, and for analytical design rules '.'-markers.

Fig. 2. Throughput as a function of the number of spatial modes for several Δn_{co} values, same optimized fibers as in Fig. 1.

impairments, this is Rayleigh scattering loss and coating loss, MBL, DMD and LMC. The channel transfer function $H[f]$ for each optimized fiber is calculated for a single span of 100 km using the multi-section model in [13] and considering a section-size of 10 m. For a $2N$ polarization mode fiber and a set of N_f frequencies, $H[f]$ becomes a $2N\times2N\times N_f$ matrix. A $N_f = 128$-long frequency vector is considered to account for the frequency dependent response along the C-band (1530-1565 nm). Using MIMO theory [14], information throughput is computed by decomposing channel (fiber) matrix $H[f]$ into a set of parallel, independent scalar Gaussian sub-channels through a singular value decomposition (SVD) and by using waterfilling power allocations for each f, given a total power constraint. The power constraint and noise variance were chosen such that the best sub-channel has a SNR of 17dB which is compatible with 100 km transmission in a power-limited scenario.

Fig. 2 shows throughput as a function of the number of spatial modes for several Δn_{co} – same optimum fibers of Fig. 1. It can be seen that, in principle, a throughput in excess of 37 Petabit/s can be reached (several times larger than the 1.5 Petabit/s over the optimized 55 spatial modes MMF in [11]). However, the spatial multiplexing gain deviates from a 1-to-1 linear gain given the increase in MDL – driven in first instance by Rayleigh scattering loss. Note that MDL scales with the number of modes, as explained in Section II. Also, in Fig. 2, it can be seen that throughput can decrease with N-modes after peaking for a large N, specifically, $N = 1081$ at $\Delta n_{co} = 0.04$. At this point, MBL and coating loss become dominant even for the 2nd to last mode group, see [9] for more details. Further analysis has shown that for this optimized fiber, and if ranking modes per achievable throughput, the 10% worst modes have only half of the throughput of the 10% best modes – hence we name $N = 1081$ (at $\Delta n_{co} = 0.04$) as the half-mode number of graded-index multimode fibers.

IV. Conclusions

We reviewed the design of graded-index trench-assisted MMFs supporting over 1000-modes (and twice as many pol. modes) for minimum DMD in the C-band. It was shown that for a given Δn_{co}, N-modes can be scaled with w_1 without significant *DMD* degradation. And that there is margin to reach low DMD if manufacturing tolerances can be improved – over 400-modes can be supported within a *maxDMD* of 250 ps/km, typical of OM fibers at 850 nm.

We identified the achievable throughput scaling with the N-modes under Rayleigh scattering, MBL, coating loss, and linear mode coupling. Allowing for the transmission of as much as 37 Petabits/s over 100 km, assuming SNR ~17dB. Further throughput scaling introduces a strong diminishing returns regime.

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References

[1] D. J. Richardson, *et al.*, "Space-division multiplexing in optical fibres," *Nature Photonics,* vol. 7, p. 354, 2013.

[2] M. D. Feuer *et al.*, "Joint Digital Signal Processing Receivers for Spatial Superchannels," *IEEE PTL,* vol. 24, no. 21, pp. 1957-1960, 2012.

[3] B. Inan *et al.*, "DSP complexity of mode-division multiplexed receivers," *Opt. Express,* vol. 20, no. 10, p. 10859, 2012.

[4] J. X. Cai, "SDM and Parallelism in Submarine Cable Systems," in *Proc. OFC*, p. Tu3E.1, 2023.

[5] G. Rademacher *et al.*, "Randomly Coupled 19-Core Multi-Core Fiber with Standard Cladding Diameter," in in *Proc. OFC*, p. Th4A.4, 2023.

[6] A. Lobato *et al.*, "Impact of mode coupling on the mode-dependent loss tolerance in few-mode fiber transmission," *Opt. Express,* vol. 20, no. 28, p. 29776, 2012.

[7] F. A. Barbosa and F. M. Ferreira, "On a Scalable Path for Multimode SDM Transmission," *OPTICA/IEEE JLT,* vol. 42, no. 1, p. 219, 2024.

[8] L. Gruner-Nielsen *et al.*, "Few Mode Transmission Fiber With Low DGD, Low Mode Coupling, and Low Loss," *OPTICA/IEEE JLT,* vol. 30, no. 23, p. 3693, 2012.

[9] F. M. Ferreira and F. A. Barbosa, "Maximizing the Capacity of Graded-Index Multimode Fibers in the Linear Regime," *OPTICA/IEEE JLT,* vol. 42, no. 5, p. 1626, 2024.

[10] P. Sillard, *et al.*, "Rescaled Multimode Fibers for Mode-Division Multiplexing," *OPTICA/IEEE JLT,* vol. 35, no. 8, p. 1444, 2017.

[11] G. Rademacher, "1.53 Peta-bit/s C-Band Transmission in a 55-Mode Fiber," *ECOC,* p. Th3C.3, 2022.

[12] K. Takenaga *et al.*, "A large effective area multi-core fiber with an optimized cladding thickness," *Opt. Express,* vol. 19, no. 26, p. B543, 2011.

[13] F. M. Ferreira, *et al.*, "Semi-Analytical Modelling of Linear Mode Coupling in Few-Mode Fibers," *OPTICA/IEEE JLT,* vol. 35, no. 18, p. 4011, 2017.

[14] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge: Cambridge University Press, 2005.