Enabling Multimode SDM at Reduced Equalization Complexity via Optimized Elliptical Core Fibers

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ABSTRACT

We identify an optimal ovality range for elliptical multimode fiber that support 45 spatial modes. These fibers significantly reduce intramode crosstalk by 11 dB over 10 km fiber length, while minimizing the group delay spread. A 32 GBd 16-QAM dual polarization transmission over a 10 km fiber with crosstalk strength as -20 dB/km demonstrates that the DSP equalization requirements at the receiver are halved with optimized elliptical core fibers compared to circular core fibers. These findings suggest that elliptical core fibers are a promising solution for enabling low-complexity multimode fiber systems.

Keywords: Space-division multiplexing, SDM systems, Elliptical core, Multimode fibers, DSP.

1. INTRODUCTION

Space division multiplexing using multimode fibers can significantly enhance capacity by supporting multiple spatial modes, though this potential is limited by the interplay between differential mode delay (DMD) and linear mode coupling (LMC) causing group delay spread [1]. Previously, authors in [1] have explored the optimization of fiber core design parameters to have a reduced DMD in the fiber. In this work, we introduce the ellipticity in the fiber core design for the core parameters optimized in [1] to reduce the LMC along with DMD. An elliptical-shaped core means the refractive index along the major and minor axis would be different. Due to the lack of core symmetry, only hybrid modes are supported in the fiber, as a result degenerate modes split into non-degenerate modes and propagate with different effective indices. The larger the effective index difference between odd and even modes, as well as between orthogonal polarization modes, the smaller the modal coupling between them. Fig. 1 shows typical mode field distribution for a six-mode elliptical core multimode fiber (EC-MMF)– these distributions are well approximated by Hermite Gaussian (HG) modes [2].

Fibers with circular cores are initially optimized for low differential mode delay (DMD) considering a profile with a graded-index core and a cladding trench, following the procedure as in [1]. After optimization, ovality is introduced and the mode solutions to the elliptical waveguide are calculated. Ovality is defined, as as $\chi = (a - b)/\big((a + b)/2\big)$ where, a and b are the semi-major and semi-minor radius of the core [3]. For an ovality χ, the radius of the optimized circular fiber is scaled by a factor of $\sqrt{(1+\chi/2)/(1-\chi/2)}$ for a given axis and compressed by $\sqrt{(1-\chi/2)/(1+\chi/2)}$ over the respective orthogonal axis. In this way, core area and core graded exponent are maintained. The mode solutions to all waveguide

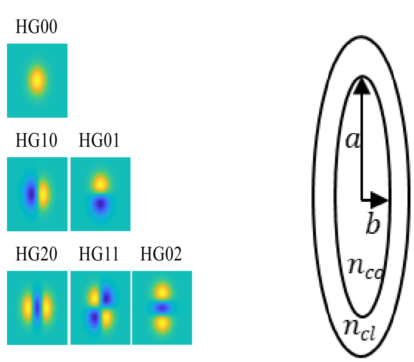

Fig. 1 Typical Hermite-Gaussian modes and fiber geometry of EC-MMF.

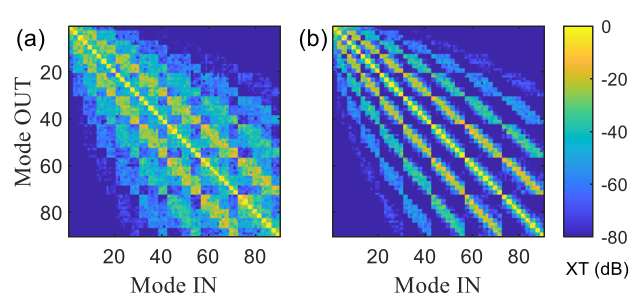

Fig. 2 Power coupling matrix for a 45-spatial mode 10 km long fiber, (a) Circular (b) 11 % ovality.

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profiles are found using the vector finite difference solver developed in [4] – a grid step of 0.2 μm and grid size of 4-times the total radius (from core center to trench end). Here, we define the fiber crosstalk as $XT_m = \sum_{v \neq m}(P_v) / (P_m)$,where P_v is the power of interfering mode v, after a given fiber segment under test, when only the spatial mode m is launched with the remaining power P_m. For the intramode group crosstalk, mode set v represents all modes within the mode group excluding from the mode of interest m. Fig. 2 shows the power coupling matrix for a 10 km long 45-spatial mode fiber with a crosstalk strength of -20 dB/km and a core-clad contrast of 0.01 with (a) circular and (b) elliptical core fiber with an ovality of 11 %. It can be observed that the coupling between modes reduces with the ovality. Previous studies of elliptical core fibers are for few numbers of spatial mode ranging from 2 to 6 over a maximum of 1 km distances [5-8]. Here, we extend the studies to 45 spatial mode fiber and to a 10 km fiber length. Previously, intra-mode group DMD study has been shown to decrease using EC-MMF [3]. Here, we study the impact of ovality on the overall DMD, and intra-mode group crosstalk. We further investigate equalization requirements for EC-MMF at the receiver for a 10 km fiber experiencing modal effects during the transmission.

2. IMPACT OF OVALITY ON FIBER CHARACTERISTICS

Initially, we investigate the impact of ovality on the DMD for the fibers already optimized for low DMD. Fig. 3 shows the maximum DMD by varying ovality for fibers with a growing number of modes – the latter is increased by increasing the fiber radius and/or the core-clad contrast (Δ) follows the trends as expected for circular fibers, discussed in [1]. Maximum DMD corresponds to the worst DMD among all mode pairs over the C-band, excluding the modes in the last mode group. Most relevant here, in Fig. 3, it can be observed that ovality has a nearly negligible impact on the maximum DMD considering circular fibers as reference, even for different core- clad contrast values and large number of modes supported in the fiber. This can be understood that ovality reduces the coupling between degenerate modes, whereas the worst DMD among all mode pairs can be between the modes from two different mode groups, and ovality didn't alter them significantly, hence maintaining the overall DMD same for all ovality values.

Further, we study the intra-mode group crosstalk for 10 km long fibers considering the multi-section case as discussed in [9], for a section length of dz = 1 m and a crosstalk strength of -20 dB/km for the fiber supporting 45 spatial modes with a core-clad contrast of 0.01. Fig. 4 shows the average intramode group *XT* over all mode groups and 500 times over fiber transmissions as a function of ovality. From the figure, the intramode group *XT* for very low ovality values below 0.5% fluctuates slightly and then decreases with increasing ovality. The intramode group *XT* remains approximately minimum for ovality values in the range of 1.5% to 11%, after which it starts to increase with the further increase in ovality. The maximum suppression of the intramode group *XT* is approximately 11 dB for the 45-mode fiber within this range of ovality values.

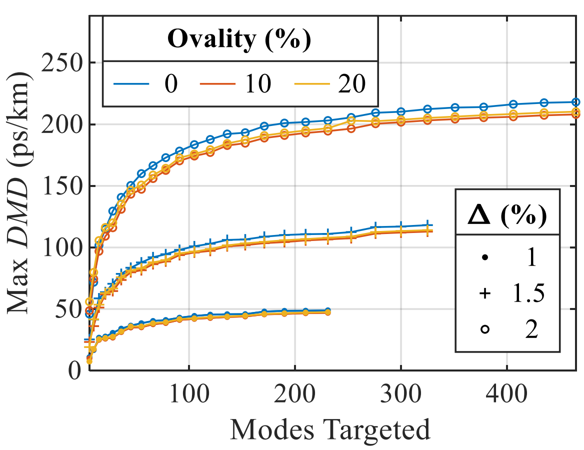

Fig. 3 Maximum DMD as a function of modes targeted in a fiber .

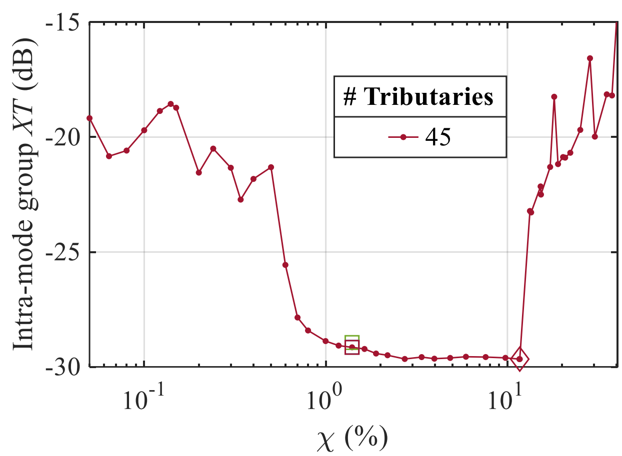

Fig. 4 Intramode group XT variation with ovality for a 10 km fiber supporting 45 spatial modes with a *XT* strength as - 20 dB/km.

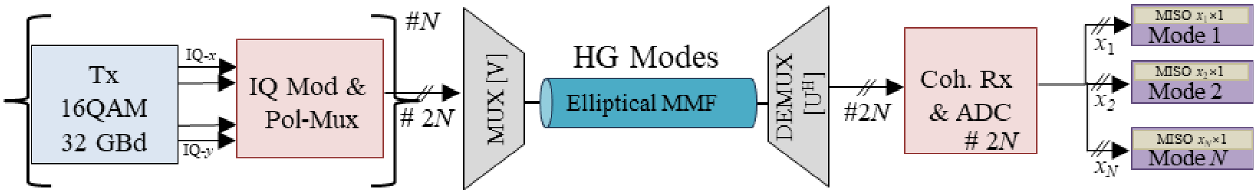

Fig.5 Simulation setup for 10 km fiber transmission over *M*-modes EC-MMF with an OSNR of 35 dB, and DSP steps used for the equalization at the receiver.

3. IMPACT OF OVALITY ON RECIVER EQUALISATION REQUIREMENTS

To analyze the impact of ovality, we consider a 32 GBd 16-QAM data transmission for the setup as shown in Fig. 5 for a 10 km 45 spatial fiber with a crosstalk strength of -20 dB/km. Before detection, amplified spontaneous emission noise is added to the signal to have an OSNR of 35 dB/0.1nm for all the detected modes. The received signal is then passed to the frequency domain multiple-input-single-output (MISO) equalizer to undo coupling effects. Since we aim to study the fiber performance here, the equalizer is supplied with the elements of the actual fiber channel – but only the coefficients corresponding to the strongest interferes are passed to the MISO equalizer. In this way, varying the MISO array size allows us to explore the equalization requirements dependence on the fiber ovality, and each mode can have unequal requirements at the receiver. Fig. 6 shows the MISO size required to recover a given tributary mode with a $SNR \geq 20$ dB – results averaged over 500 fiber realizations. The modes are sorted by MISO array requirements for convenience. From Fig. 6, it can be observed that there is an overall complexity reduction with ovality. Specifically, ovalities above 1.4 %, recover all the tributary modes for a $SNR \geq$ `20 dB with a maximum MISO size of ~12, whereas circular fibers require a maximum MISO array size of ~23. The performance remains the same as optimized ovality even for the ovality value 13.5 %, that is beyond maximum ovality value from the Fig. 4, and this requires further investigation. We calculate the complexity reduction enabled by a given ovality as the ratio of the average MISO array size required (per mode) in a circular fiber to that required for the corresponding elliptical fiber. Overall, the maximum complexity reduction averaged over all modes of 1.8 times is obtained for the ovality values beyond 1.4%.

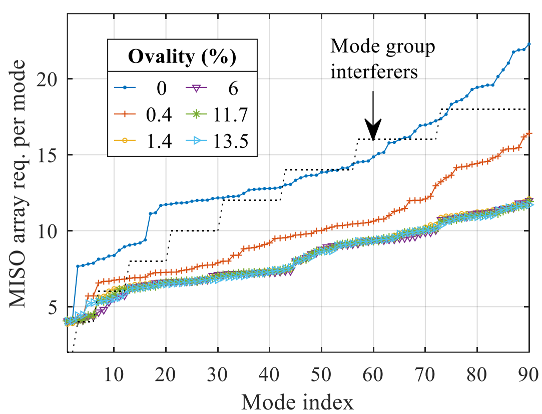

Fig. 6 .MISO array required per mode to achieve 20 dB *SNR* for a 10 km 45 spatial mode fiber with *XT* as -20 dB/km.

4. CONCLUSIONS

In summary, an optimal ovality range is identified for EC-MMFs. Given DMD optimized circular MMFs, their intramode group *XT* can be suppressed by as much as 11 dB at the end of 10 km with a 45-spatial mode transmission. For an SDM transmission system, the MIMO-DSP requirement is significantly reduced, by a factor of ~1.8-times. These findings identify a potential solution for low complexity multimode SDM systems.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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