On the Impact of Spatial Mode Dispersion for Strongly-Coupled Multicore Fiber Submarine Transmission

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Abstract: Strongly-coupled multicore fibers exhibit the improved tolerance to fiber non-linearity. Their potentials in optical submarine communications are investigated with considering the coupling length and spatial mode dispersion.

1. Background

Optical submarine communication cables carry a huge amount of communicating data, so it is of great significance to the modern big-data industries. Two main challenges to realize the high capacity of optical submarine cables are: 1) Feeding power to the cable repeaters is provided by the stepped voltage between shores, so the power saving at high capacities is very important and difficult. 2) Fiber nonlinearity would be severe due to the ultra-long haul transmission across ocean. To solve the above issues, it has been theoretically proved to be efficient by utilizing the space division multiplexing (SDM) based on multiple SMFs [1]. The advantages of using multiple SMFs can be attributed to two reasons: 1) SDM scales the capacity with an approximately linear relationship to the optical power, outperforming a SMF link which complies with the logarithm relationship between the capacity and the optical power. 2) The reduced power density due to the increased spatial diversity results in less fiber nonlinearity. Comparing to the multiple SMFs solution, utilizing SDM with multicore fibers (MCF) can be more compact which could result in a smaller cross-sectional area of submarine cables. As a result, the MCFs-based submarine cables exhibit certain potentials when fiber pair count is constrained due to the mechanical limitations during the cable design [2]. Additionally, the strongly-coupled MCF (SC-MCF) could further reduce the fiber nonlinearity impact thanks to the random mode coupling among cores. However, the spatial mode dispersion (SMD) of SC-MCFs leads to the inter-core skew of optical paths in every cores. It places a heavy burden to multiple-input and multiple-output (MIMO) DSP, because the interplay of inter-core crosstalk (IC-XT) and inter-core skew will widen the pulse response of submarine cables.

In this paper, we conducted a submarine transmission model based on coupled nonlinear Schrodinger equations (CNSE) with self examinations of IC-XT and SMD. Based on concrete simulations, we investigate the transmission performance of 4-core SC-MCF based optical submarine cables for C-band transmissions with comprehensive considerations of fiber nonlinearity, IC-XT and SMD, with the limited feeding power and fiber pair count.

2. Optical submarine transmission model based on coupled nonlinear Schrodinger equations

Nonlinear fiber transmission can be well described by the Manakov equation [3]. For the optical field transmitted in core A $\boldsymbol{E_A}$ which containing two polarization states, the filed evolution over the longitudinal coordinate and time with the coupling from core B can be described by the CNSE as follows [4],

$$\frac{\mathrm{d}\boldsymbol{E}_A}{\mathrm{d}z} = -\frac{\alpha}{2}\boldsymbol{E}_A + \beta_1 \frac{\mathrm{d}\boldsymbol{E}_A}{\mathrm{d}t} + \frac{\beta_2}{2}\frac{\mathrm{d}^2\boldsymbol{E}_A}{\mathrm{d}t^2} + \frac{\beta_3}{6}\frac{\mathrm{d}^3\boldsymbol{E}_A}{\mathrm{d}t^3} + j\frac{8}{9}\gamma\boldsymbol{E}_A^3 - jk_{AB}\exp(-j\Delta\beta_{AB})\boldsymbol{E_B}, \tag{1}$$

where α is the fiber attenuation coefficient, β_1, β_2, β_3 represent the propagation constant, the group velocity dispersion and the dispersion slope, respectively. γ represents fiber nonlinearity coefficient and k_{AB} is coupling strength which can be associated to the coupling length L_c by $k_{AB} = 1/L_c$. In addition, the phase matching condition to accomplish mode coupling is emulated by Gaussian random process modeling of $\Delta\beta_{AB}$. We solve the Eq. (1) by the split-step Fourier method (SSFM) with a fine step size which should be smaller than the coupling length L_c.

To ensure the convincing results drawn by the conducted fiber transmission model, the self examinations of IC-XT and SMD have been performed. As shown in Fig. 1, the single span transmission at 100 km is examined by measuring the IC-XT and pulse reponses at the end of cable, referring to the manually set values of IC-XT and SMD. Due to the random characteristic of the phase matching condition to realize mode coupling, the measured IC-XT values should be derived by their mean values with certain variances. The measured mean values of IC-XT match the set values well, as indicated in Fig. 1(a). By setting the SMD at 1ps/km, the real part of the received pulses (turning off the fiber nonlinearity) in X polarization of two cores with Lc at 10000 km are given in Fig. 1(b). The relative delay between two cores at 100 ps indicates that the modeling of 1-ps/km SMD is accurate. The strong coupling leads to the Gaussian-like shape of pulse responses, as given by Fig. 1(c), and the widened pulse response places a heavier burden to the MIMO DSP which requires longer taps to demodulate the coupled fields.

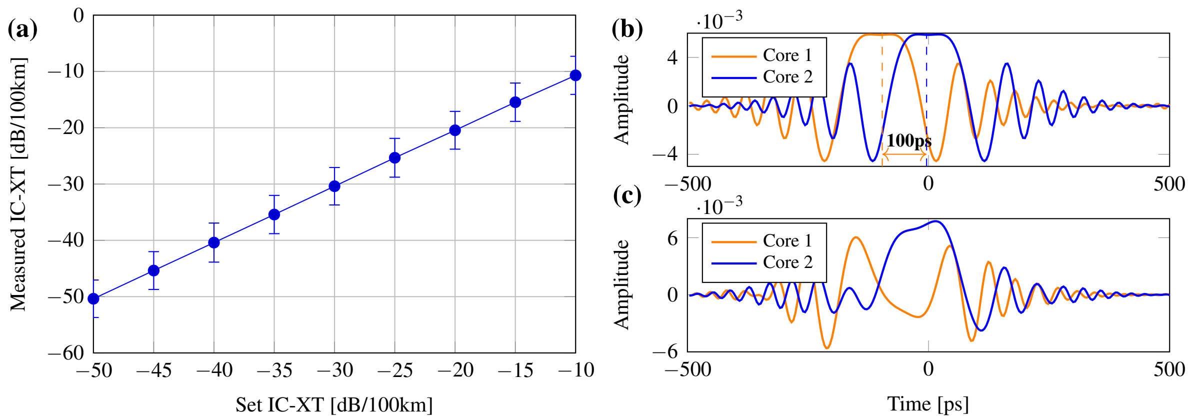

Fig. 1. The self-examinations of the conducted transmission model for the single span 100 km case. (a) Measure IC-XT values against the sett values. (b) Pulse responses (the real component of optical fields in X polarization) in two cores with 100 ps SMD and L_c at 10000 km and (c) at 100 m.

3. Results

Main systematic settings of the submarine cables are given in Table 1. Span length at 54 km has been theoretically proved to be optimal to achieve a compromising performance between fiber nonlinearity suppression and ASE accumulation [5]. Fiber attenuation at 0.16 dB/km corresponds to the ultra-low loss fiber characteristic. 4-core MCFs are investigated over the Atlantic and the Pacific with distances of 6000 km and 11000 km, respectively. 80 carriers with 53 GHz spacing are modulated by independent DP-QPSK signals at 50 Gbaud. Considering the fiber pair count and feeding power limitations in submarine cables, we recorded Q factors averaging over all spatial modes under varied circumstances as shown in Fig. 2.

Table 1. Simulation parameters

TX Parameters	
Symbol rate	50 Gbaud
No. of channels	80
Channel spacing	53 GHz
Modulation format	DP-QPSK
Amplifier bandwidth	4.3 THz
Fiber and Link Parameters	
The Atlantic cable length	6000 km
The Pacific cable length	11000 km
Span length	54km
Attenuation coeff.	0.16 dB/km
Disp. parameter	16 ps/nm/km
Nonlinear coeff. (γ)	0.81 W/m
Amplifier noise figure	5 dB
Fiber pair count	8

It can be indicated by Fig. 2 that the improved tolerance to fiber nonlinearity can be achieved by using 4-core

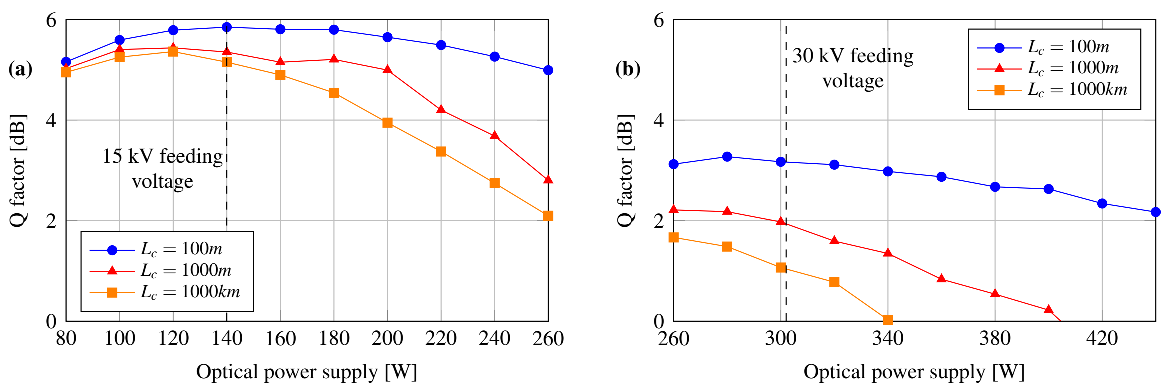

Fig. 2. Q factors vs. optical power supply for the submarine cables with 8 pairs of 4-core MCF over (a) the Atlantic and (b) the Pacific.

SC-MCFs. Optical power supplies at 140.6 W and 306.8 W to the trans-Atlantic and -Pacifc cables correspond to the feeding voltages at 15 kV and 30 kV respectively, with assuming 1.5% E/O efficiency of repeaters. In these conditions, 4-core SC-MCFs with L_c at 100 m could offer 0.7- and 2.1 dB Q factor gain to the weakly-coupled MCFs ($Lc = 1000$ km) for the trans-Atlantic and -Pacific cases, respectively.

Pulse broadening of optical fileds transmitted over SC-MCFs due to SMD will place a heavy burden for MIMO-DSP to recover individual tributaries. However, the propagation constant of individual cores of MCFs is heterogeneous when the cores suffers different conditions of micro bending and twist. In this case of the strongly-coupling regime with L_c at 100 m, Q factor values vs. SMD results for the trans-Atlantic and trans-Pacific are given in Fig. 3(a). Inserted figures are the constellations in the cases of 40 ps/100km Atlantic cable and 56 ps/100km Pacific cable, respectively. As shown in Fig. 3(b) and (c), pulse broadening can be indicated by the spreading of 8×8 MIMO taps. 8×8 MIMO taps are trained by 10000 prior-known sequences using the least mean square error strategy. Due to the limited tap number of MIMO-DSP, the equalization performance is degraded when SMD is over 50 ps/100km for the Pacific cable.

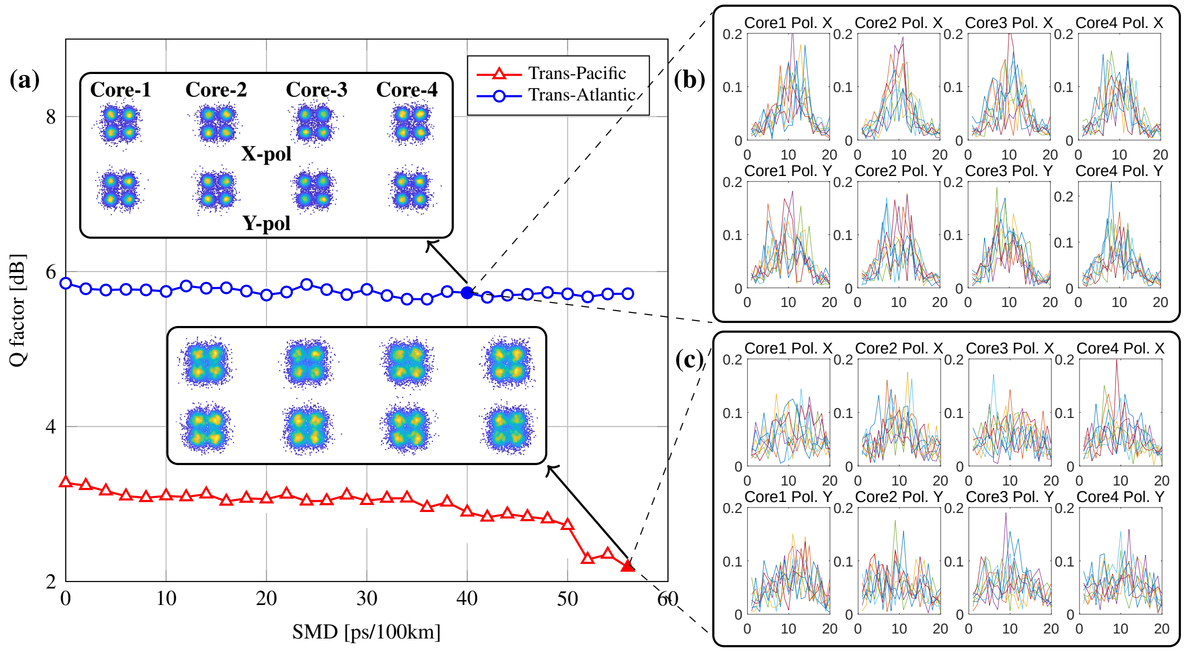

Fig. 3. (a) Q factors vs. SMD curves, and inserted figures are typical constellations. Convergent taps for (b) the Atlantic cable with 40 ps/100km SMD and (c) the Pacific cable with 56 ps/100km SMD.

4. Conclusion

We investigate the potentials of 4-core SC-MCFs in optical submarine communications, as well as the SMD impacts to the transmission performance. Strong coupling among cores of SC-MCFs is beneficial to the nonlinearity suppression for long-haul fiber transmissions. At the 50 Gbaud rate, up to 50 ps/100km SMD can be tolerated to demodulate the coupled fields by using the 20 taps 8×8 MIMO DSP for the Pacific cable.

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References

1. R. Dar, P. J. Winzer, A. R. Chraplyvy, S. Zsigmond, K-Y Huang, H. Fevrier, and S. Grubb, "Cost-optimized submarine cables using massive spatial parallelism," J. Light. technology **36**(18), 3855–3865 (2018).
2. J. D. Downie, X. Liang, and S. Makovejs, "Assessing capacity and cost/capacity of 4-core multicore fibers against single core fibers in submarine cable systems," J. Light. technology **38**(11), 3015–3022 (2020).
3. P. K. A. Wai, and C. R. Menyak, "Polarization mode dispersion, decorrelation, and diffusion in optical fibers with randomly varying birefringence," J. Light. technology **14**(2), 148-157 (1996).
4. T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," Opt. Exp. **19**(17), 16576-16592 (2011).
5. A. Pilipetskii, M. Bolshtyansky, D. Foursa, and O. Sinkin, "SDM power-efficient ultra high-capacity submarine long haul transmission systems (tutorial)," In 2020 Optical Fiber Communications Conference and Exhibition (2020).