Comparisons between weakly- and strongly-coupled multicore fibers for the submarine optical communications

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***Abstract*—The potentials of weakly- and strongly-coupled multi-core fibers in the submarine communications are comparatively investigated. Random coupling among cores leading to super-mode transmission in submarine fibers is beneficial to the signaling performance of MIMO-DSP.**

***Index Terms*—Optical submarine communications, multi-core fibers, digital signal processing**

I. Introduction

The practical design of optical submarine communication cables has to carefully consider the cable weight and size, so that limits the accommodated fiber count. As a consequence, multi-core fibers (MCFs) are able to further increase the capacity thanks to space division multiplexing (SDM). Illustration of the MCFs-based submarine cable across the sea is given in Fig. 1. Due to the power supply to the cable repeaters is fed by the voltage difference between shores, the submarine cable is also optical power limited. Under these two limitations, SDM linearly scale the capacity with using more spatial paths, so that outperforms the SMF link whose capacity approximately complies with the logarithmic relationship to optical power. The power saving of submarine cables has been theoretically proved to be efficient by SDM using the MCFs ribbon [1]. On the other hand, fiber nonlinearity can not be neglected even for the power limited submarine cable because the transmission distance is over several thousands of kilometers. The reduced power density by SDM results in less fiber nonlinearity, which in return boosts the upper bound of power supply.

However, the loss induced by MCFs as well as the multi-core devices less or more shrinks the above advantages of the MCFs solution to submarine cables. Inter-core crosstalk (IC-XT) is an issue for weakly-coupled MCFs (WC-MCFs) based submarine cables, in which case SDM is treated as the individual transmitted tributaries of polarization-multiplexed signals. IC-XT performs as a random noise in this case. Employing MIMO-DSP at the receiver can mitigate IC-XT, then more cores with much closer pitch can be accommodated in a standard cladding. The named strongly-coupled MCFs (WC-MCFs) possess the ability to guide the super-mode, which shows advantages of lower spatial mode dispersion (SMD) [2] and reduced fiber nonlinearity [3]. The key characters of heterogeneous cores in SC-MCFs limiting the performance of MIMO-DSP includes SMD, mode dependent loss (MDL) [4], which even increase the outage probability of communicating.

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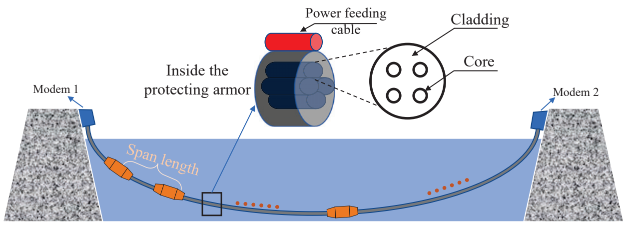

Fig. 1. Illustration of the MCFs-based submarine cable.

This paper presents our recent theoretical works to model the WC-MCFs and SC-MCFs submarine cables, including the optimization based on GN model and the transmission performance evaluation based on coupled nonlinear Schrodinger equation (CNSE). Results indicate that the stronger coupling of SC-MCFs is beneficial to the transmission performance of submarine cables. However, the tap length of MIMO-DSP should be chosen appropriately for addressing the SMD issue. Our future work would focus on the outage performance of submarine cables influenced by SMD and MDL.

II. Optimization of Cable Mechanical Parameters

The cable mechanical parameters influencing the overall capacity mainly includes span length l and the accommodated spatial path M. Capacity (in two directions) of a submarine cable can be formulated by Eq. (1).

$$C = 2 \cdot M \cdot B \cdot \log_2(1 + SNR) \tag{1}$$

where, B is the amplifiers' bandwidth, SNR is the cable end-to-end SNR, M is the *bidirectional* spatial path that equals to the production of fiber pair count M_{fiber} and core number per fiber M_{core}. Considering the signal droop effect, the corresponding capacity estimation can be further written as

$$C = 2 \cdot B \cdot M \cdot \log_2(\frac{P_{tot}}{N \cdot M \cdot P_{ase+NLN}}). \quad (2)$$

N is the repeater number, P_{tot} is optical power supplied by all repeaters. Neglecting the nonlinear term in $P_{ase+NLN}$ and substituting it by $(e^{\alpha l}F - 1)hvBN$ (α is the fiber attenuation coefficient, F is the amplifier's noise figure. h is Plank's constant. v is the central frequency of the ASE spectrum), we can get

$$C = 2 \cdot B \cdot M \cdot \log_2(\frac{P_{tot}}{B \cdot M \cdot N^2 \cdot (e^{\alpha l}F - 1)hv}). \quad (3)$$

From Eq. (3) we can know that $C(B \cdot M)$ is convex, and the global maximization can be achieved when $B \cdot M = \frac{4P_{tot}}{(e^3F-e)\cdot hv(L\cdot\alpha-2)^2}$. MCFs solution could alleviate the requirement of the broad band WDM modulation and amplification.

According to Eq. (2), l affects the power density of ASE noise P_{ase} by $P_{ase} = (e^{\alpha l}F - 1)hvBN$. Then we could define the function $N \cdot P_{ase}$ as $F(l)$, which is also convex. So the optimal value can be found with $F'(l) = 0$. Then, the optimal span length can be obtained by $l = 2/\alpha$. For the manufactured G.654E optical fibers, the optimal l is at 54km.

Based on the above derivations, the optimal $B \cdot M$ equals to $\frac{4P_{tot}}{(e^3F-e)\cdot hv(L\cdot\alpha-2)^2}$ and N equals to $\frac{\alpha L}{2} - 1$. Then we can get the corresponding SNR is $e - 1$. That corresponds to the DP-QPSK formats with the input entropy of 4. In addition, the forward error corrections (FEC) are also mandatory for correcting the errors the transmitted signals in submarine cables.

III. Comparisons between SC- and WC-MCFs Submarine Cables

Based on the above-stated optimization strategies, span length of the 6000-km submarine cable is set at 54km. And modulation format is chosen as DP-QPSK. Fiber count limitation is typically considered with 8 pairs of MCFs accommodated. For emulating the C80 system by the CNSE model (detailed fiber parameters see [5]), 80 subcarriers are modulated by 50-Gbaud PDM-QPSK signals with the 53-GHz spacing, so those cover the 4.3-THz spectrum. We emulate 5 adjacent subcarriers for XPM and SPM effects. With a sufficient optical power supply at 240W to the trans-Atlantic cable (6000km) with 8 pairs MCFs, corresponding constellation diagrams with coupling length at 1000km and 100m are presented in Fig. 2. As indicated by Fig. 2, the stronger coupling of MCFs results in the improved performance. MCFs with coupling length at 1000km have individually transmitting cores, in which mode coupling only occurs between two polarization modes. In the case of coupling length at 100m, mode coupling occurs among all cores thus DSP requires 8-by-8 MIMO to demodulate signals. It can be indicated by Fig. 3 that the improved tolerance to fiber nonlinearity can be achieved by using 4-core SC-MCFs than WC-MCFs.

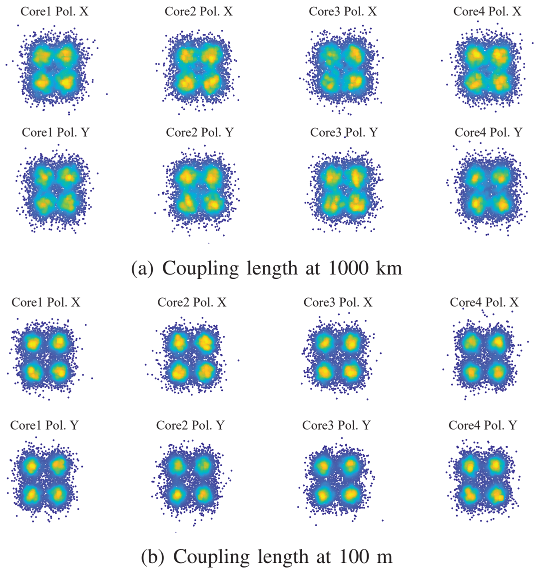

Fig. 2. Constellation diagrams for the 8-pair MCFs cable with optical power supply at 240W, with coupling length at 1000km (a), 100m (b).

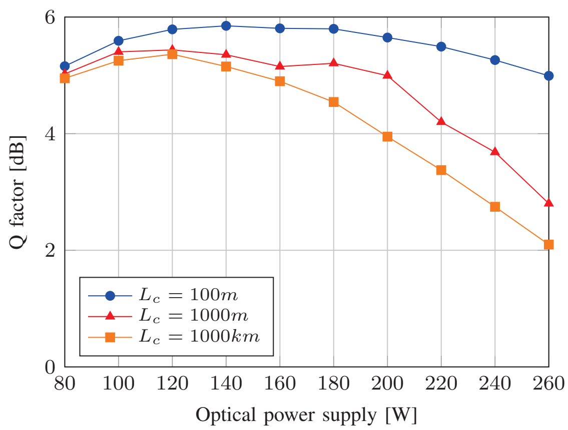

Fig. 3. Q factors vs. optical power supply for the submarine cables with 8 pairs of 4-core MCFs.

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 suffer 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 (6000km) and trans-Pacific (11000km) are given in Fig. 4. Due to the limited tap number (20 taps) of MIMO-DSP, the equalization performance is degraded when SMD is over 50 ps/100km for the Pacific cable.

IV. Conclusion

We comparatively investigate the performances of WC-MCFs and SC-MCFs for the submarine communications based on simulations. Thanks to the random coupling among coupled cores, SC-MCFs outperforms WC-MCFs with alleviated fiber

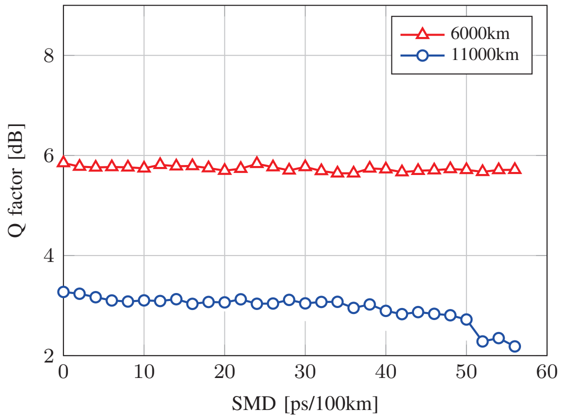

Fig. 4. Q factors vs. SMD curves fot the trans-Atlantic and trans-Pacific cables respectively.

nonlinearity. However, SMD and MDL of the heterogeneous cores places challenges to SC-MCFs to achieve longer transmission distance. We would extent our work to study the statistical characters of SMD and MDL in randomly-coupled cores, and investigate their impacts on the outage probability of the submarine cables.

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