Impact of Linear Mode-Coupling on Nonlinear Performance of Long-haul Strong-Coupled Multicore Fibers Transmission

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Abstract— **We adapt Gaussian-noise (GN) model to evaluate the nonlinear performance of strong-coupled multicore fibers (MCFs) transmission. An expression for the nonlinear interference is obtained taking into account the linear mode-coupling. Our results show that linear mode-coupling can mitigate the nonlinearity effect in MCFs.**

Keywords— **Gaussian noise (GN) model, multicore fibers (MCFs).**

1. Introduction

The capacity crunch of single mode fibers (SMFs) motivates the research for new degrees of freedom to enhance the optical transmission capacity [1]. Space-division multiplexing (SDM) using either multimode fibers (MMFs) or multicore fibers (MCFs) shows a window to solve this capacity crunch [2]. A major source of system performance limitation in long-haul fiber transmission is the nonlinear interaction between different cores (modes) [3, 4]. Various MCFs designs are proposed to mitigate this nonlinear effect [2]. Moreover, the strong-coupled MCFs would be a way to reduce the nonlinear interference penalty on the system performance [5]. In recent years, several experimental efforts are done in long-haul SDM-based transmission [2]. Moreover, extensive research efforts are presented to characterize the nonlinear propagation in long-haul fiber transmission either through numerical simulation [3–5] or analytical modeling [6–9]. Gaussian-noise (GN) model is an effective anlytical tool for addressing the nonlinear performance of hybrid wave-division multiplexed and space-division multiplexed (WDM/SDM)-based systems [8, 9]. To the best of our knowledge, the GN-model is not applied in strong-coupled MCFs transmission. Moreover, the linear mode-coupling effect has not been taken into account in GN-model yet.

In this paper, based on our previous work [6], we formulate a closed-form expression for the nonlinear interference in strong-coupled single-mode MCFs taking into consideration the linear mode-coupling. The effect of the linear coupling level as a function of the number of cores in long-haul MCFs is discussed as well.

2. Modified GN-model for Multicore Fibers

The pulse propagation of dual-polarized signal in a nonlinear dispersive strong-coupled single-mode MCFs is described by the adapted nonlinear Schrödinger equation (NLSE) as [5]:

$$\frac{\partial \bar{\mathbf{A}}_p}{\partial z} = -\frac{\alpha}{2}\bar{\mathbf{A}}_p + \mathrm{j}\beta(f)\bar{\mathbf{A}}_p + \mathrm{j}\sum_{m\neq p} q_{mp}\bar{\mathbf{A}}_m + \mathrm{j}\frac{\gamma}{3}\sum_{lmn} f_{lmnp} \times \left[\left(\bar{\mathbf{A}}_l^T * \bar{\mathbf{A}}_m\right) * \bar{\mathbf{A}}_n^{\star} + 2\left(\bar{\mathbf{A}}_n^H * \bar{\mathbf{A}}_m\right) * \bar{\mathbf{A}}_l\right], \quad (1)$$

where $\bar{\mathbf{A}}_p(z,f)$ is the mode field envelope within a core with index p, α and $\beta(f)$ are the core attenuation coefficient and dispersion term, respectively, and γ is the fiber nonlinearity coefficient. The superscripts: $\star$, T, and H are conjugate, transpose, and Hermitian operator, respectively. $q_{mp} = \pi/(2L_c)$ is the linear mode-coupling coefficient between any two core with indices (m,p), where L_c is the coupling length, and f_{lmnp} is the nonlinear tensor among different modes, and its intra-modal term ($f_{pppp} = 1$) is dominant over the inter-modal ones as in [5].

GN-model treats the nonlinear interference as independent source of additive Gaussian noise (GN) that is statistically independent from both amplifier noise and the transmitted signal [6, 8–10]. Therefore, the per-core performance of MCFs can be determined by the optical signal-to-noise ratio as: $\mathrm{OSNR}_p = P_{tx}/\left(P_n + P_{nl_p}\right)$, where P_{tx} is the average-injected power per core, P_n is the noise power, and P_{nl_p} is the nonlinear interference power among different cores. For erbium-doped fiber amplifier (EDFA), the noise power is amplified-spontaneous-emission (ASE) noise which is expressed as $P_{\mathrm{ASE}} \approx F(G-1)h\nu B_n N_s$, where F is the amplifier noise figure, G is the amplifier gain, h is Plank's constant, ν is the center channel frequency, B_n is the noise bandwidth of 12.48 GHz (0.1nm), and N_s is the number of fiber spans. Following a similar procedure as [6, 8, 10], we adapt the GN-model for long-haul strong-coupled single-mode MCFs transmission. After a rigorous mathematical analysis, we obtain an analytical expression for the nonlinear interference power as:

$$P_{nl_p} \approx \frac{3}{8\pi}\frac{\gamma^2}{|\beta_2|}\frac{L_{\mathrm{eff}}^2}{L_{\mathrm{eff,a}}}\frac{B_n}{B_{ch}^3}N_s \operatorname{arcsinh}\left(\frac{3\pi^2|\beta_2|L_{\mathrm{eff,a}}B_{ch}^2N_{ch}^2}{8\left[1+\left(L_{\mathrm{eff,a}}\sum_{m\neq p}q_{mp}^2\right)^2\right]}\right)P_{tx}^3, \quad (2)$$

where β_2 is the group-velocity dispersion (GVD) parameter, $L_{\mathrm{eff}} = (1-e^{-\alpha L_s})/\alpha$ and $L_{\mathrm{eff,a}} = 1/\alpha$ are the effective and asymptotic effective lengths of a fiber with a span length L_s, respectively. Furthermore, B_{ch} is the channel bandwidth and N_{ch} is the number of the WDM channels.

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3. Results and Discussions

The proposed model is studied over homogeneous strong-coupled single-mode MCFs that has the following parameters: $\alpha = 0.22$ dB/km, $D = 17$ ps^2/km, $\gamma = 1.5$ W^{-1}km^{-1} [5], and a total fiber length of 1000 km with a span length of 100 km. The cores are arranged so that the linear mode-coupling coefficients are equal. The coupling length L_c is taken to be 200 m. The QPSK/WDM specifications are: Baud rate of 28.5 GBaud (a net data rate of 25 GBaud +14% for forward error correction (FEC) [10]). A single-channel WDM system is considered, with a channel bandwidth of $B_{ch} = 28.5$ GHz. The used EDFA has a noise figure of 6 dB and a gain that compensates for the span loss, i.e., $G = e^{2\alpha L_s}$.

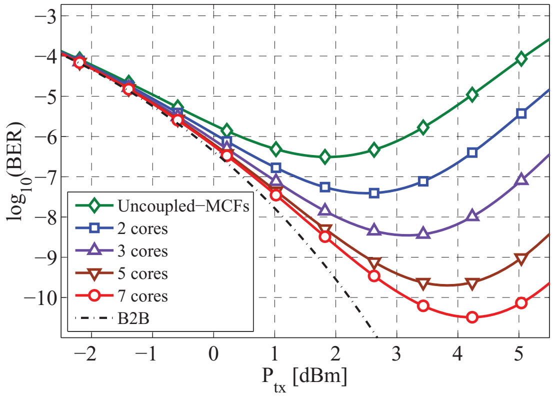

Fig. 1: Average BER versus average-injected power per core for different number of cores compared with uncoupled MCFs.

Figures 1 and 2 depict the effect of increasing the linear mode-coupling level (by increasing the number of cores) on the nonlinear performance of strong-coupled single-mode MCFs transmission. It is worth mentioning that all the linear impairments (dispersion and linear coupling) are equalized by means of digital signal processing at the receiver side [5]. In Fig. 1, we plot the average BER for a single-channel dual-polarized QPSK/WDM/SDM system as a function of the average-injected power per core. The results of strong-coupled MCFs transmission are compared to that of both uncoupled and back-to-back (B2B) transmissions. It can be seen that an increase in the number of cores beats the deleterious effect of nonlinearity on the system performance. This can be explained as follows. The higher coupling level on a specific core signal, the faster variations in its propagated power. These variations have a similar impact as the chromatic dispersion effects, that results in coping the nonlinear performance limit in MCFs transmission. Specifically, at optimal nonlinear performance, increasing the number of cores to 2 and 7 enhances the BER by about 1 and 4 order of magnitudes, respectively, when compared with the uncoupled MCFs transmission.

Furthermore, Fig. 2 illustrates the linear mode-coupling effect on the maximum reach at the FEC-requirement (BER $= 10^{-3}$). It is found that the optimal maximum reach is extended by increasing the number of cores. Compared to the uncoupled MCFs transmission, the relative reach improvement is about 925 km and 8500 km corresponding to 2 and 7 cores, respectively. Our results are in a reasonable agreement with [5].

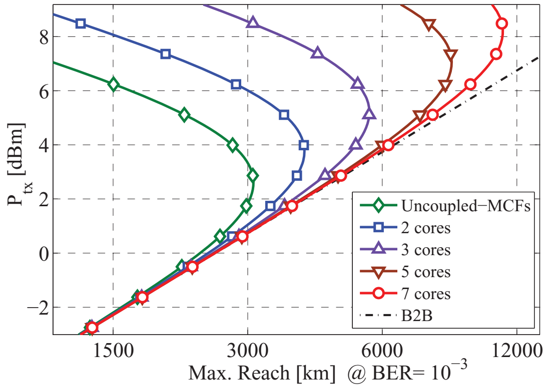

Fig. 2: Average-injected power per core versus maximum reach for different number of cores compared with uncoupled MCFs.

4. Conclusion

An adapted GN-model has been used to evaluate the long haul strong-coupled single-mode MCFs transmission. A closed-form expression for the nonlinear interference power has been presented taking into account the linear mode-coupling. Our results reveal that linear mode-coupling can beat the nonlinearity limit in SDM-based systems. These results are in agreement with the literature conclusion.

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