COUPLED-CORE FIBER DESIGN FOR ENHANCING NONLINEARITY TOLERANCE

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Abstract: Fiber nonlinearity is a major limitation on the achievable maximum capacity per fiber core. Digital signal processing (DSP) can be used directly to compensate nonlinear impairments, however with limited effectiveness. It is well known that fibers with higher chromatic dispersion (CD) reduce nonlinear impairments, and CD can be taken care of with DSP. Since, maximum CD is limited by material dispersion of the fiber we propose using strongly-coupled multi-core fibers with large group delay (GD) between the cores. Nonlinear mitigation is achieved through strong mode coupling, and group delay between the cores which suppresses four-wave mixing interaction by inducing large phase-mismatch, albeit stochastic in nature. Through simulations we determine the threshold GD required for noticeable nonlinearity suppression depends on the fiber CD. In particular, for dispersion-uncompensated links a large GD of the order of 1ns per 1000 km is required to improve optimum Q by 1 dB. Furthermore, beyond this threshold, larger GD results in larger suppression without any signs of saturation.

1. INTRODUCTION

Fiber nonlinearity is a major limitation on the achievable maximum capacity per fiber core. Digital signal processing (DSP) can be used directly to compensate nonlinear impairments through digital back propagation (DBP) [1]. However, maximum amount of improvement is ultimately limited because of the presence of amplifier noise, and only self-phase modulation can be mitigated. This is the case even when sufficient DSP resources are available.

Another approach is to mitigate nonlinear penalties at the expense of inducing linear impairments which can be more easily removed with coherent DSP [2-4]. The advantage of this approach is that, nonlinear mitigation can be increased beyond what can be achieved through DBP, as long as sufficient DSP resources are available. Increasing fiber chromatic dispersion (CD) is a good example [3], however, maximum CD is limited by material dispersion of the fiber. Another example is polarization-mode dispersion (PMD) which was shown to be effective in the case of dispersion compensated links [4]. Even though PMD is more difficult to equalize compared to the fixed CD, it can be easier to engineer a fiber with large PMD, and therefore obtain larger nonlinear mitigation beyond what could be achieved by the largest CD that can be obtained.

In this letter, we show by simulations that fibers can be designed with strong mode coupling and large modal group delay (MGD) that can mitigate fiber nonlinearity beyond that can be obtained by DBP as long as sufficient DSP resources are available.

Two cases are studied by simulation for dispersion uncompensated links. The first case is a single-mode, single-core fiber with extremely large polarization mode dispersion (LPMD). The second case is CC-MCF with two strongly coupled single-mode cores, which is already shown to suppress nonlinear impairments [5-6] even without modal delays. Here the analysis is extended to include the impact of large modal delay. The LPMD fiber would be compatible with existing transmission systems, however, it would require extremely high DSP resources. The advantage of the CC-MCF is that they would require less MGD for the same amount of nonlinearity mitigation as LPMD fibers, however, significant changes in the transmission system would be necessary, such as fan-in fan-out devices [6].

2. MODELING STRONG MODE COUPLING AND MODAL DELAY IN LPMD FIBER AND CC-MCF

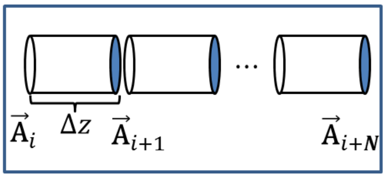
Both cases are modeled using the standard coarse step method [7]. Fiber is modeled as a concatenation of uniform sections, where the modes propagate independently, with a fixed modal delay between them. Between each section, the modes are rotated randomly. In the case of PMD, the two modes represent the polarization modes, and in the case of CC-MCF, the two modes represent the two cores. As depicted in Figure 1, Manakov equation (ME) is solved using split step Fourier Transform method (SSFT), where mode coupling and modal delay are induced at each step.

In Fig.1, $\vec{\boldsymbol{A}}_i = [A_{1x}\, A_{1y}\, A_{2x}\, A_{2y}]^T$ is the optical field propagating in the two cores with two polarization modes in the case of CC-MCF, and $\vec{\boldsymbol{A}}_i = [A_{1x}\, A_{1y}]^T$ in the case of LPMD fiber, at the i[th] step. $\mathbb{N}_i$ is the nonlinear operator at the i[th] step, $P_k^i = |A_{kx}|^2 + |A_{kx}|^2$, n=1,2 corresponds to single core LPMD, and 2 core CC-MCF respectively, γ is the nonlinearity parameter, Δz is the step size, $I_{n\times n}$ is the n by n identity matrix. $\mathbb{D}_i(\omega)$ is the dispersion operator, where β_2 is the dispersion parameter which is assumed to be the same for both cores in the CC-MCF. M_i is either a 2x2, or a 4x4 random unitary matrix that would uniformly mix the two polarization modes of the LPMD fiber, or the two polarization modes of both cores of the CC-MCF. $\mathbb{T}_i(\omega)$ is the modal delay operator with $\beta_1^i = \left(1/v_{g1}^i - 1/v_{g2}^i\right)$ where v_{g1}^i and v_{g2}^i are defined as either the group velocities of the polarization modes in the case of LPMD fiber, or the group velocities of two cores in the case of the CC-MCF. In order to avoid spurious peaks from artificial periodicity of the concatenation, β_1^i is implemented as a random variable fluctuating around a mean value of $\langle\beta_1^i\rangle$ with a standard deviation equal to the 20% of the mean value. The mean MGD which results from the modal delay between the coupled cores, and the differential group delay (DGD) in the case of LPMD is related to both $\langle\beta_1^i\rangle$ and the number of total steps in the link as

$$MGD = \langle\beta_1^i\rangle\sqrt{L\Delta z/2} = \langle\beta_1^i\rangle\Delta z\sqrt{N/2} \quad (1)$$

where, L is the total length of the span, and N is the total number of steps. The underlying assumption is that, the coupling length between the polarization modes are much shorter than the coupling length between the two cores. Therefore, any signal launched into any of the polarization modes in either of the cores would be equally spread to all four possible modes at the length scale of the coupling length between the two cores.

In order to see the impact of modal coupling, and modal delay on nonlinearity, transmission of a single channel dual-polarization 64QAM channel with 43 GHz baud-rate, is simulated over a link with 10 spans. Even though only a single channel is simulated to reduce the simulation time,



$$\vec{\mathbf{A}}_{i+1} = \mathbb{N}_i M_i \mathcal{F}^{-1}\{\mathbb{T}_i(\omega)\,\mathbb{D}_i(\omega)\mathcal{F}\{\vec{\mathbf{A}}_i\}\} \qquad \mathbb{D}_i(\omega) = e^{j\frac{1}{2}\beta_2\Delta\omega^2\Delta z}$$

$$\mathbb{N}_i = \begin{bmatrix} e^{j\frac{8\gamma}{9}P_1^i\Delta z} I_{n\times n} & 0_{n\times n} \\ 0_{n\times n} & e^{j\frac{8\gamma}{9}P_n^i\Delta z} I_{n\times n} \end{bmatrix} \qquad \mathbb{T}_i(\omega) = \begin{bmatrix} e^{j\frac{\beta_1{}^i\Delta\omega\Delta z}{2}} I_{n\times n} & 0_{n\times n} \\ 0_{n\times n} & e^{-j\frac{\beta_1{}^i\Delta\omega\Delta z}{2}} I_{n\times n} \end{bmatrix}$$

Figure 1: Schematic explaining the modeling of the nonlinear transmission in the LPMD fiber and CC-MCF fiber.

similar nonlinear mitigation is expected even with WDM case. The link parameters are as follows; span length is 100 km, fiber attenuation is 0.2 dB/km, nonlinearity parameter is 1.16 W^{-1} km^{-1}, amplifier noise figure is 5 dB. To see the interplay between the fiber CD and required amount of DGD, and MGD, CD value is varied. In the case of CC-MCF all the fiber parameters are assumed to be identical for both cores. Simulation window is fixed at 2^{12} symbols in time domain, and 4 times the channel baud-rate in the frequency domain. Because the purpose is to see how the fiber design affects fiber nonlinearity, the DSP is kept at a minimum at the receiver side. All the transmission matrices used in the forward propagation are saved, and they are used to completely compensate the modal coupling, and delay. Q factor obtained from bit error counting is used to assess the signal degradation.

3. SIMULATION RESULTS AND DISCUSSION

First, the LPMD fiber is simulated. Fig2a shows the Q factor as a function of channel power. CD is changed from 21 ps/nm/km to 5 ps/nm/km, and then to 80 ps/nm/km. Even though such a large dispersion is not realistic, it is used to demonstrate the dependence of Q improvement due to MGD to the level of chromatic dispersion. As expected, the Q value increases both with increasing CD and DGD due to reduction of nonlinear penalty.

However, since it is difficult to increase CD beyond the material dispersion of fiber, increasing DGD may be the better way to mitigate nonlinearity as long as it can be effectively equalized with DSP. Indeed, this benefit of PMD was noticed earlier resulting from the residual birefringence, however it was concluded that PMD can reduce nonlinearity only in dispersion compensated systems [4].

Here it is shown that, PMD would help in dispersion uncompensated links, as long as DGD is large enough which can only be achieved by intentionally inducing large birefringence. In the simulated example in Fig2a, 1.1 ns DGD requires a beat length of ~3cm that can be obtained by elliptical core fibers [8], and birefringence coherence length on the order of 100 m.

The improvement can be seen more clearly in Fig2b which shows how the maximum Q changes with increasing DGD, with the dashed lines corresponding to the case without PMD for reference. When CD is large, for instance at 21 ps/nm/km, small levels of DGD does not improve the Q value, and DGD at low levels is effective only when CD is low which agrees with previous reports

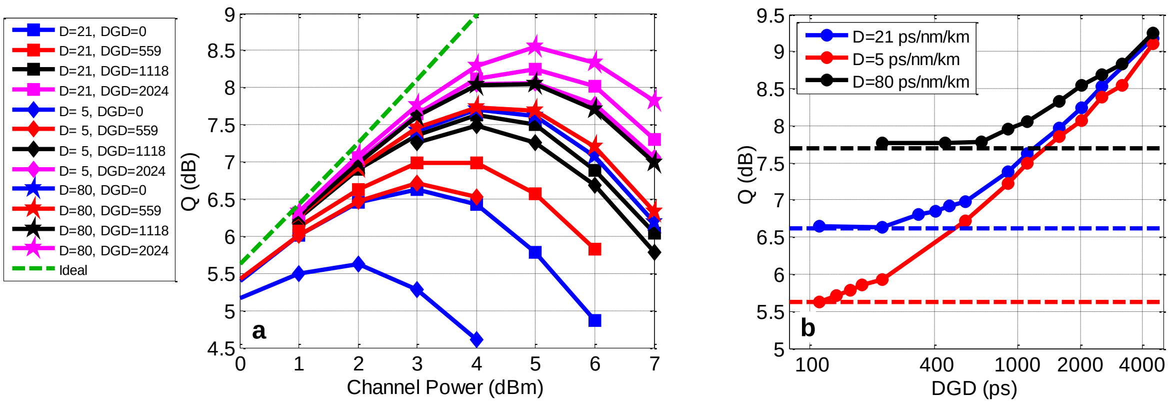


Figure 2: Large PMD fiber simulation results. a) Q versus channel power for different levels of DGD, for fibers with three different dispersion parameters, 21 ps/nm/km (square), 5 ps/nm/km (diamond), and 80 ps/nm/km (stars). DGD has units of ps. Green line shows the ideal Q value expected due to the received SNR from amplifier noise only. b) Maximum Q versus DGD for the three chromatic dispersion values. Dashed lines show the maximum Q for DGD=0.

[4]. At the same time it shows that, if DGD can be increased substantially, no matter what the fiber CD is DGD will reduce nonlinear impairments. Figure 2b also shows that, at large DGD, nonlinearity mitigation is dominated by DGD, and Q factor converges for all CD values. Moreover, for the simulated range of DGDs, there is no sign of saturation of Q improvement.

converge at the high MGD limit. As a practical example, 5 ns DGD on Fig3b can be achieved in coupled-core fiber with the local group delay difference between the cores ~1.26 ns/km requiring an index difference on the order of $3.8x10^{-4}$ which can be easily achieved [6] with a coupling length on the order of 31 m, which can be controlled by the distance between the cores.

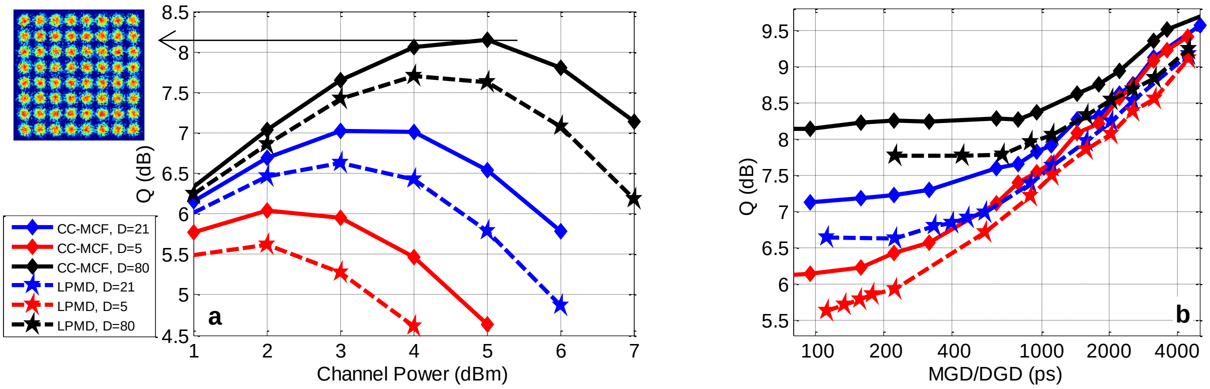


Figure 3: Comparison of CC-MCF to large PMD fiber. a) Q versus channel power with both MGD=DGD=0, and for three different dispersion parameters, 21 ps/nm/km (blue), 5 ps/nm/km (red), and 80 ps/nm/km (black). b) Maximum Q versus MGD for three different dispersion values.

Simulations are repeated for two-core CC-MCF, and the results are compared with the LPMD fiber in Fig3. In Fig3a, Q vs channel power is plotted for both fibers with the same three CD values and without any modal delay. Note that in the case of LPMD, DGD=0 corresponds to standard single-mode fiber. In the case of CC-MCF, there is a clear advantage in terms of nonlinearity [5,6]. Because ME is solved independently for the two cores, and their effective areas are assumed to be the same, this mitigation of nonlinearity originates purely from the random coupling between the cores [5,6]. This mitigation remains regardless of CD. In Fig 3b, maximum Q is plotted as a function of MGD, and compared to the LPMD. Similar to the case of LPMD, large MGD helps to mitigate nonlinearity even further. Again, for fibers with larger CD, a larger MGD is required to see this additional benefit. Similar to the case of LPMD, at larger MGD, Q improvement is dominated by MGD rather than CD, and all the curves

In terms of reducing nonlinear impairments, CC-MCF has an advantage since it does not require large MGD to obtain a modest but noticeable Q improvement [5,6]. For instance, in the simulated case shown in Fig 3b, the LPMD requires close to 1 ns DGD in order to have similar Q improvement as CC-MCF without MDG. On the other hand LPMD would be compatible with existing single-mode single-core transmission system architecture. It should also be noted that, in case a large MDG/DGD is desired, it would be easier to obtain a larger MGD using CC-MCF than obtaining large DGD with a single-core fiber. Conversely, it may not be easy to obtain very low MGD in the case of CC-MCF.

4. CONCLUSIONS

Nonlinearity mitigation in the case of CC-MCF with and without large modal group delay is shown through simulations, and it is compared to nonlinearity mitigation in the case of a single-core fiber with large DGD. It is shown that PMD can reduce nonlinear impairments even in dispersion uncompensated links as long as the DGD is large enough. CC-MCF provides Q improvement at a much reduced modal group delay compared to large PMD fiber.

5. REFERENCES

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