Four-Wave Mixing in Optical Phase Conjugation System with Pre-Dispersion

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***Abstract*—We mathematically analyze Kerr-induced fiber nonlinearity in an optical communication system using mid-link optical phase conjugation and pre-dispersion. The derived analytical expressions are used to describe the system performance and show great matching with simulations. Furthermore, based on these expressions, we predict the performance of a transmission system and prove a 3dB improvement in Q-factor compared to the OPC system without pre-dispersion.**

I. Introduction

Optical Phase conjugation (OPC) is an all optical method for simultaneous mitigation of chromatic dispersion and nonlinearity impacts in single mode fiber (SMF). It is based on reversing the phase of the transmitted signal at the middle of the link, while dispersion and Kerr-induced nonlinear effects are compensated for during propagation in the second half of the link [1]. However, in order to achieve perfect dispersion and nonlinearity compensation using mid-link OPC, the power profile and dispersion need to be symmetric with respect to the OPC. One method to achieve the power symmetry is using short span lengths which means closely spaced amplifiers and further cost, and energy consumption [2]. Another approach where the Raman amplification can be also used to enhance the power symmetry [3].

In this context and as an alternative, Minzioni et. al. proposed in [4] the addition of suitable dispersive elements before or after OPC to enhance the power symmetry only in the regions of the link where signals propagate with higher power (right after the lumped amplifiers). From graphical analysis, they concluded that the maximum compensating efficiency occurs for using dispersive elements with accumulated dispersion of $-D(L-L_{eff})$, where D and L are the transmission fiber dispersion coefficient and span length respectively and L_{eff} is the effective length. In this paper, to the best of our knowledge, for the first time, signal-signal nonlinearity in mid-link OPC system with lumped amplification and pre-dispersion before OPC has been mathematically analyzed. The analytical result has been validated through simulation. In addition, we have used the analytical formula to predict the performance of a transmission system and the results show that the Q-factor of the transmission of 224Gbps PM-16QAM system over 10 spans of 100 km SMF has been improved by 3dB due to the pre-dispersion and fully in accordance with the analytical predictions.

II. Four-Wave Mixing in Pre-Dispersed OPC System

To analyze the four-wave mixing (FWM) power generated in mid-link OPC system with lumped amplification and pre-dispersion, we assume, a system with N spans, length L, dispersion β_2 and attenuation (α), which is completely compensated with an amplifier after each fiber span. An ideal phase conjugator is placed at the middle of the link and an extra dispersion compensation fiber (DCF) is added before the OPC. The nonlinearity from DCF is ignored for simplicity. Using the conventional approach [5] after considering the effect of multiple spans, OPC and DCF, an analytical formula for the idler power from three signal frequencies f_1, f_2, and f_3 with powers P_1, P_2, and P_3 respectively can be written as,

$$P_f = \frac{4D_g\gamma^2 P_1P_2P_3}{9(\alpha^2+\Delta\beta^2)^2}\frac{\sin^2(N\Delta\beta L/4)}{\sin^2(\Delta\beta L/2)}\kappa^2, \quad (1)$$

$$\kappa = \alpha(e^{-\alpha L}\sin[(\Delta\beta L-\Delta\beta_1L_1)/2]+\sin[(\Delta\beta L+\Delta\beta_1L_1)/2]) + \Delta\beta(e^{-\alpha L}\cos[(\Delta\beta L-\Delta\beta_1L_1)/2]-\cos[(\Delta\beta L+\Delta\beta_1L_1)/2]).$$

Where γ and α are the nonlinear coefficient and attenuation factor of SMF respectively. L_1 is the length of DCF and $\Delta\beta$ is the phase mismatch term between the three signals in the transmission fiber and for standard SMF can be approximated by considering only the second order dispersion β_2 as, $\Delta\beta =$-$4\pi^2\beta_2(f_1-f_3)(f_2-f_3)$ and $\Delta\beta_1$ is the equivalent phase mismatch for the DCF. D_g represents the degeneracy factor and equal to 3 if $f_1=f_2$ and 6 if $f_1\neq f_2$. Setting $L_1=0$ gives the FWM power for a conventional OPC system [6], and setting $k^2=\frac{1}{4}(1-e^{-\alpha L})^2+e^{-\alpha L}\sin^2(\frac{\Delta\beta L}{2})$ and $N=(2N)$ provides the FWM power for a system without OPC [7]. The impact of pre-dispersion is expressed through the symmetry efficiency κ, and is minimized for each combination of signal frequencies for a certain value of $\Delta\beta_1L_1$.

In order to calculate the total nonlinearity affecting the signal, we assumed that f_1 is the signal and f_2 and f_3 are interferes. The total FWM power can be calculated by double integrating of Eq. (1) over the signal bandwidth [8]. The integration was solved numerically and the signal to noise ratio (Q-factor) were calculated by dividing the signal power over the sum of amplifier linear noise and total FWM power, assuming that the nonlinear power distribution is Gaussian [8].

III. Simulation Results

A. Four-Wave Mixing Power

In order to validate Eq. (1), a simulation was run using VPITransmissionMaker 9.5 by transmitting two continuous wave (CW) laser signals with 0 dBm powers in 10x100km SMF with dispersion coefficient, attenuation and nonlinear coefficient equal to 16 ps/nm/km, 0.2 dB/km and 1.3 $(w.km)^{-1}$ respectively. The simulation was run with 8 samples per symbol. An ideal OPC (no insertion loss or frequency conversion) was implemented in Matlab. The FWM powers were measured at the end of the link at different frequency separations (Δf) between the two CW lasers. Figure (1) shows two different cases; no pre-dispersion (red) and pre-dispersion of opposite-sign to and magnitude of $(L - L_{eff})D$.

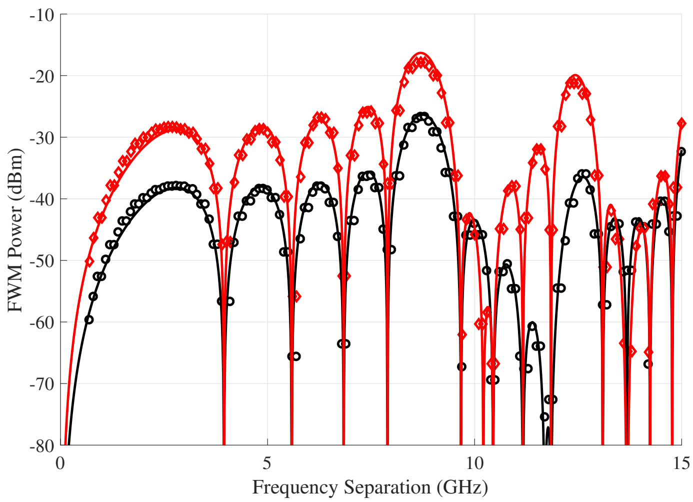

Fig. 1: FWM power of OPC system as a function of frequency separations between the two signals in two cases: without pre-dispersion (red) and with pre-dispersion (black) for theory (lines) and simulation (markers).

The solid lines represent Eq. (1) and the symbols represent the simulation results are clearly showing an excellent match between theory and simulation. Figure (1) shows that the FWM power is eliminated by the OPC in both cases in the the strongly phase matching region. For the weakly phase matched contributions, FWM power is typically suppressed by around 10 dB due to the in-line dispersion 1256 ps/nm. In addition, the pre-dispersion affects the FWM efficiency and does not affect the phase array which cause the lopes.

B. The Performance of PM-16QAM in Pre-Dispersed OPC System

Using the same transmission link, we simulated the performance of 224 Gbps PM-16QAM operating at 193.1 THz. We used VPITransmissionMaker 9.5 for fibre transmission and Matlab for signal recovery and performance measurement. The transmitted bits was 2^{20} bits per polarization, and the modulated optical signals was simulated with 8 samples per symbol. The PMD and dispersion slope were ignored to focus on the nonlinearity compensation. Erbium-doped fiber amplifiers (EDFA) were used with 6dB noise figure. The Q factor was measured from error vector magnitude (EVM). Figure (2) shows the Q-factor as a function of the fibre input power, in the two scenarios and compared theory (solid lines) with simulations (symbols).

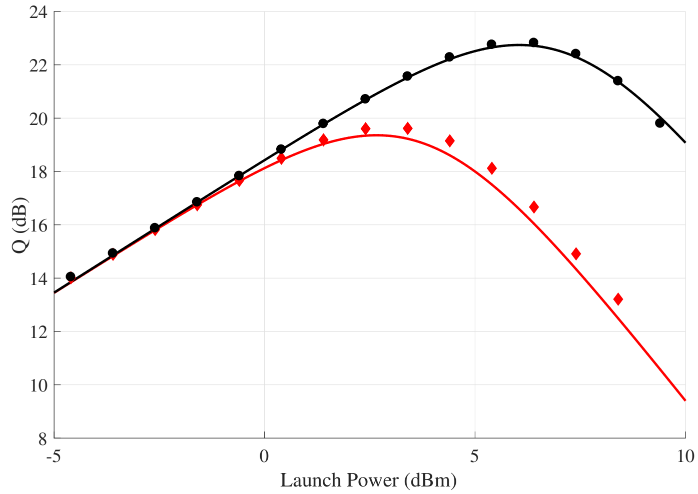

Fig. 2: The Q-factor of 224Gbps PM-16QAM transmitted over 10x100km SMF link incorporating an OPC as a function of the launched power in two cases: without pre-dispersion (red) and with pre-dispersion (black) for theory (lines) and simulation (markers).

The results show that the pre-dispersion will produce an improvement in Q-factor measured at the optimum power about 3 dB compared with OPC system without DCF. The simulation results closely match the theoretical curves with an error less than 0.3 dB measured at the optimum Q value. Figure (3) shows the maximum Q factor for different link lengths with 100 km span lengths and different number of spans with consistent 3 dB improvement due to the pre-dispersion.

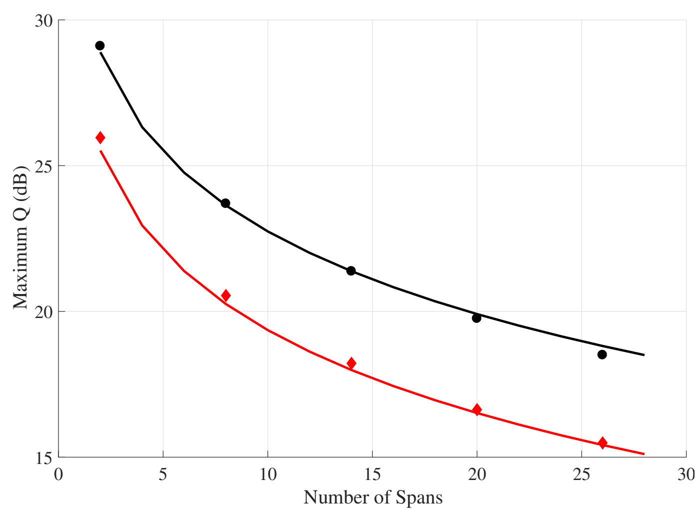

Fig. 3: The maximum Q factor as a function of the link length with 100 km span length in two cases: without pre-dispersion (red) and with pre-dispersion (black) for theory (lines) and simulation (markers).

IV. Conclusion

An analytical expression for the FWM power in mid-link OPC system with pre-dispersion has been introduced. The analytical model has been verified through numerical simulation. In addition, it has been used to predict the performance of 224 Gbps PM-16QAM transmission system, where the results show that a Q-factor improvement of 3 dB can be achieved using a DCF before the OPC.

Acknowledgement

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