Impact of polarization-mode dispersion and fiber nonlinearities on four-wave mixing efficiency

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Abstract
The paper describes the impact of XPM and SPM on the FWM efficiency. Also the influence of PMD is evaluated. The accumulation of FWM along the spans is investigated for different inline dispersion compensation schemes.

1 Introduction
Four-wave mixing is one of the major degradation effects in WDM systems with dense channel spacing and low chromatic dispersion on the fiber. If in a WDM system the channels are equally spaced, the new waves generated by FWM will fall at the channel frequencies and give rise to crosstalk. FWM is often isolated from the other nonlinear effects both in numerical simulations as well as analytical models. However, the FWM phase-matching factor is dependent on the signal power [1]. For the first time to our knowledge it is shown that this effect is also relevant for long-haul transmission systems with relatively low channel input powers. Also the dependence on the inline dispersion compensation scheme is investigated. Furthermore, the influence of PMD on the FWM process is analyzed. It is well known that PMD reduces the FWM efficiency in a single span [2]. In this paper we show how the accumulation of the FWM products along the spans is changed by PMD.

2 Simulation Setup
The analyzed transmission system consists of eight channels with a frequency separation of 50 GHz. The modulation format is NRZ-OOK with a line rate of 10 Gb/s. The channel input power into each span is 0 dBm. The center channel has been left away to measure the generated FWM power at that position. The transmission fiber is an NZDSF with \( D = 2 \text{ ps/(nm-km)} \) and \( l = 100 \text{ km} \). The dispersion slope has been neglected \( (S=0) \). The inline dispersion compensation has been varied between 0, -25 and -40 ps/nm/span. The split-step Fourier (SSF) method has been used to solve the nonlinear Schrödinger equation. A logarithmic step distribution with 145 steps has been considered. Additionally 100 steps have been inserted to model PMD using a waveplate model [3]. The number of split-steps is sufficient to suppress the artificial FWM peaks for the chosen system parameters [4].

3 Impact of fiber nonlinearities on FWM efficiency
A total distance of 2000 km (20 spans) has been simulated (Fig. 1). The ratio of the measured FWM power at the vacant center channel to the power of a signal channel has been chosen as a figure of merit. A value of -25 dB is often chosen as a limit for transmission systems.

Fig. 1. Simulated FWM-Signal Power ratio for the center channel.
As expected a full-inline dispersion compensation (0 ps/nm/span) leads to the highest FWM power. Also an undercompensation of -25 ps/nm/span yields relatively high FWM degradations. FWM can be suppressed quite efficiently for an undercompensation of -40 ps/nm/span.

This is in line with the experimental results shown in [5]. If additionally SPM and XPM are taken into account (dashed lines in Fig. 1), the FWM power shows a slight deviation from the pure FWM results especially for
higher span counts. In Fig. 2 the impact of the inline dispersion compensation on a system with 20 identical spans is depicted. The FWM power after the first span has to be multiplied by $S_{FWM}$ to yield the FWM power after 20 spans. For the case of constructive interference this value converges to $N^2$, where $N$ stand for the number of spans. This also explains the qualitative behavior of the FWM accumulation. For 0 and -25 ps/nm/span relatively high peaks occur in Fig. 2 indicating high FWM degradation. XPM and SPM change the FWM phase-matching factor slightly. This leads to a small deviation from the depicted undercompensation. The difference between the curves with and without fiber nonlinearities in Fig. 1 is higher for 0 and -25 ps/nm/span because of the sharp peaks in Fig. 2 and remains relatively low for the flat region around -40 ps/nm/span.

### 4 Impact of polarization-mode dispersion

Beyond taking into account the other nonlinear fiber effects, also considering the effect of PMD is important for a more realistic assessment of a real system. In the following it is investigated how PMD affects the accumulation of FWM along the spans. In Fig. 3 the results for two different dispersion compensation schemes, -25 (top) and -40 ps/nm/span (bottom), are depicted. For the simulation 100 waveplates per span have been assumed. Their position is randomly fluctuating with a Gaussian distribution and a standard deviation of 15%. Because of the high computational effort required for nonlinear SSF simulations it was not possible to use Monte-Carlo simulations. Instead three random realizations were chosen leading to a good approximation for most cases. However, the tails of the DGD distribution are not reached. In Fig. 3 only one realization is depicted for the purpose of clarity. Qualitatively no large deviations for the other realizations could be observed.

![Fig. 3. Simulated FWM-Signal Power ratio for the center channel incorporating PMD and fiber nonlinearities.](image)

It can be seen that for an undercompensation of -25 ps/nm/span the highest FWM degradations are obtained in the case without PMD. For PMD values of either 0.05 ps/sqrt(km) representing newer fibers or 0.1 ps/sqrt(km) standing for legacy fibers, the FWM power is clearly reduced. If, however, -40 ps/nm/span compensation is chosen, the accumulated FWM values obtained for fibers with PMD are slightly higher than without PMD, despite the reduced FWM efficiency in a single PMD fiber span. This shows that for an exact FWM analysis the fiber nonlinearities and PMD should always be included.

### References