XPM-INDUCED INTENSITY NOISE IN WDM COMPENSATED TRANSMISSION SYSTEMS

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Abstract: A new linear model of the XPM-induced intensity noise is used for a fast evaluation of the system degradation at the end of several types of dispersion compensated transmission systems.

Introduction

In dispersion compensated systems the intensity distortion induced by the interplay between cross-phase modulation (XPM) and group velocity dispersion (GVD) can be a primary cause of transmission degradation. Like any phase noise, XPM generates intensity distortion at the end of a dispersive fiber [1], but because of its distributed generation, compensation cannot perfectly undo such distortion. In this paper we give the expression of a linear filter that accounts for the intensity/cross-phase/intensity conversion (IM/XPM/IM) at the end of any type of dispersion compensated system. This allows a fast computation of the XPM-induced intensity noise at the receiver, without resorting to very long simulations, so that it becomes a very useful tool in the design of terrestrial long-haul wavelength division multiplexed (WDM) transmission systems.

Theory

We consider an N-channel WDM system propagating over a transmission fiber of length L_1 followed by a compensating fiber of length L_2. In [3] we gave an explicit expression of an IM/XPM filter in the general case of dispersion compensated systems, capable of very well predicting the reference signal phase. In presence of chromatic dispersion, the XPM contribution generated at a given point along the fiber is converted by GVD into intensity modulation during the propagation from that point to the end of the fiber [1]. Assuming all the contributions of each infinitesimal segment add up to build the total intensity noise, the global XPM-induced relative intensity variation at the end of the span is:

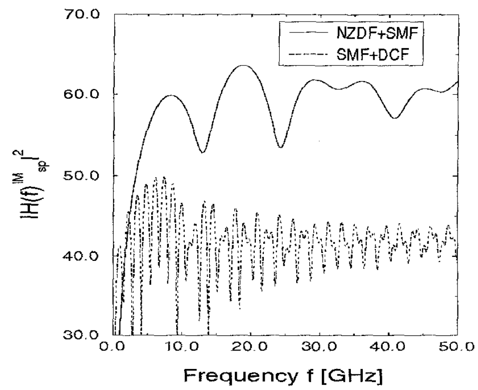
$$\frac{\Delta P_s(\omega)}{\langle P_s \rangle} = -2\gamma \sum_{p \neq s} P_p(0,\omega)\, H_{sp}^{IM}(\omega)$$

where <Ps> is the time averaged input signal power, γ is the fiber nonlinear coefficient, $P_p(0,\omega)$ the Fourier transform of the p-th input channel power, and $H_{sp}^{IM}(\omega)$ is the total IM/XPM/IM filter for the p-th interferer. In the special case of perfect compensation at channel s, and neglecting nonlinear effects in the compensating fiber, such filter simplifies to:

$$H_{sp}^{IM}(\omega) = j\left\{ \left(\frac{1-\exp\left[\left(-\alpha_1 + j\left(d_{sp}\omega - \Psi\omega^2\right)\right)L_1\right]}{\alpha_1 - j\left(d_{sp}\omega - \Psi\omega^2\right)} \right) - \left(\frac{1-\exp\left[\left(-\alpha_1 + j\left(d_{sp}\omega + \Psi\omega^2\right)\right)L_1\right]}{\alpha_1 - j\left(d_{sp}\omega + \Psi\omega^2\right)} \right) \right\} \quad (1)$$

where $\Psi = \lambda^2 D_1 / 4\pi c$, λ being the central wavelength and c the light velocity; D_1, α_1, and d_{sp} are the chromatic dispersion, the attenuation coefficient, and the walk-off parameter between channels s and p [2], respectively, of the transmission fiber. Equation (1) can be easily extended to the general case of a system composed of M amplified and compensated links, without neglecting the compensation fiber contributions [4].

Fig. 1: Squared magnitude of the IM/XPM/IM filter. Channel separation 0.8 nm



As an example, Fig.1 gives the squared magnitude of $H_{sp}^{IM}(\omega)$ for a single compensated span, with perfect compensation at channel s, for two different compensating schemes. In the first scheme (solid line), the transmission fiber is a non-zero dispersion fiber (NZDF), with D_1 = -2 ps/nm/km, L_1=85 km, and the compensating fiber is a single mode fiber (SMF) with D_2=17 ps/nm/km and L_2= 10 km. Other parameters common to the two fibers are the dispersion slope D'= 0.07 ps/km/nm^2, γ=2.35 W^{-1} km^{-1} and α=0.21 dB/km. In the second scheme (dashed line), the transmission fiber is a SMF as above, with L_1=57 km, and a dispersion compensating fiber (DCF) with D_2=-95 ps/nm/km, L_2=10.2 km, D'=0.07 ps/km/nm^2, γ_2=6 W^{-1}km^{-1}, α_2=0.6 dB/km is used for compensation. We clearly see that the XPM filtering action is more effective in the SMF+DCF scheme, where the walk-off parameter is larger [2,3].

Results

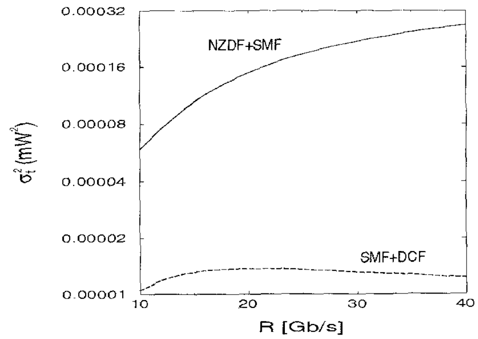
We used the theoretical model to obtain the XPM noise variance on channel s at the receiver as:

$$\sigma_t^2 = 4\gamma^2 \langle P_s \rangle^2 \int_{-\infty}^{\infty} S_p(0,\omega) \left| H_{sp}^{IM}(\omega) \right|^2 d\omega$$

where $S_p(0,\omega)$ is the spectrum of the interferer power on channel p. For a single span perfectly compensated system,

Fig.2 shows σ_t^2 versus the bit rate R of the p channel for both of the previous compensation schemes.

Fig. 2: σ_t^2 versus bit rate.



The peak power of both channel s and p is 5 dBm, the channel spacing is $\Delta\lambda$=0.8 nm, and channel p is on-off keying (OOK) modulated with nonreturn-to-zero (NRZ) raised cosine pulses (roll-off 0.8). The variance is larger for the NZDF+SMF scheme, being the IM/XPM/IM filter stronger in this case, as confirmed by Fig.1. The variance also grows monotonically in the range shown, while in the SMF+DCF scheme the variance has a maximum and then decreses for higher bit rates. This is a direct consequence of the shape of the IM/XPM/IM filter plotted in Fig.1.

Fig. 3: σ_t^2 versus degree of compensation for two different systems.

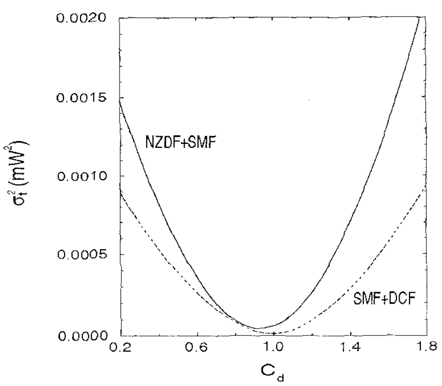
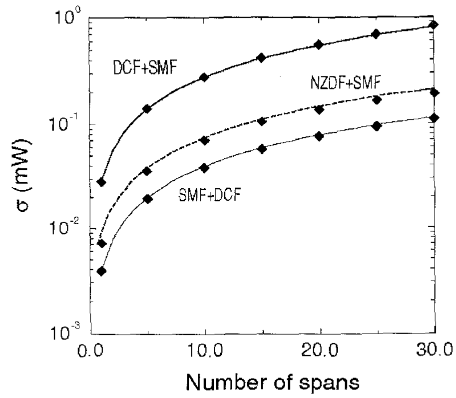


Fig.3 shows a plot of σ_t^2 versus the degree of dispersion compensation, defined as $C_d=|D_2L_2/D_1L_1|$. In this case we kept L_1 fixed and varied the length L_2. For a single span and the power levels used, a slight undercompensation (C_d<1) minimizes the XPM-induced intensity distortion for the SMF+DCF scheme, while more undercompensation is needed to optimize the NZDF+SMF scheme.

Simulations based on the split-step Fourier method (SSFM) were carried out to verify the goodness of the theoretical predictions. Three WDM channels, with 5 dBm peak power per channel and $\Delta\lambda$=0.8 nm spacing, with a CW probe central channel and two 10 Gb/s modulated edge channels were propagated along a chain of span-by-span compensated and amplified links. The compensation schemes were: 1) NZDF+SMF and 2) SMF+DCF as described before; and 3) DCF+SMF, where we swapped the position of the transmission and compensating fiber in scheme 2). Exact compensation was achieved at the CW channel.

We consider the power variation induced by XPM on the probe channel and we define the sample variance as $\sigma^2=(1/N)\sum_{k=1}^{N}[P_s(kT_0/N)-\langle P_s\rangle]^2$ where P_s is the channel power and N=8192 is the number of samples in the observation time T_0 corresponding to 128 bits. In Fig.4 we plot σ versus the number of compensated spans both for simulations (solid line) and for our model (diamonds). As we see from the figure, the IM/XPM/IM theoretical model well predicts the output probe power variations. Note that, for a single simulation with M=30 spans, the SSFM takes 10 hours on a SUN workstation, while our linear model takes 5 min. Note also that the DCF+SMF system, which has been shown to be the best dispersion map in the case of single channel propagation [5], gives the worst performance with respect to XPM effects.

Fig. 4: σ versus number of spans in three different maps. Solid: simulation; Diamonds: theory.



Conclusion

A linear filter that accurately describes the XPM-induced intensity noise in WDM systems is presented. Our IM/XPM/IM theoretical model gives accurate predictions of the output intensity distortions over terrestrial transmission distances, so that it can be used as a quick design tool.

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