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Statistical Study of Cross-Phase Modulation in Multi-Span IMDD WDM Systems

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Cross-phase modulation (XPM) is an important source of performance degradation in WDM optical fiber systems. As reported previously, the XPM-induced crosstalk in uniform-dispersion fiber links depends on fiber dispersion, optical signal channel spacing and the number of amplified optical spans [1]. In practical systems, installed fiber links are made of short fiber spools each with a different zero-dispersion-wavelength (λ_0) [2]. Because of the statistical properties of λ_0 distribution along the fiber link, the XPM impairment is expected to be different from ideal uniform fiber links. To find the worst-case system impairment is crucial for practical system performance evaluation.

Consider a probe and a pump channel copropagating in the same fiber. XPM-induced intensity crosstalk from the pump to the probe, originated from one short fiber segment of length L', can be evaluated at the end of the fiber $z = L$ by

$$\Delta \tilde{A}_j(\Omega, L) = \sqrt{p_j(L)}\, e^{-i\Omega L'/v_j} \gamma\, p_k(\Omega,0) \int_0^{L'} e^{-(\alpha - i\Omega d_{jk})z} \sin[\beta_2 \Omega^2 (L-z)/2]\, dz \qquad (1)$$

where subscribes j and k indicate the probe and the pump, respectively. $p_j(L)$ is the probe channel average optical power at the end of the system. $p_k(\Omega,0)$ is the power spectrum of the pump signal at the system input. γ is the nonlinear coefficient and β_2 is the chromatic dispersion of the fiber. v_j is the group velocity of the probe channel. $d_{jk} = S_0(\lambda - \lambda_0)\Delta\lambda_{jk}$ is the relative walk-off between the two signals, where λ_0 and S_0 are fiber zero- dispersion wavelength and dispersion slope respectively, and $\Delta\lambda_{jk}$ is the wavelength separation between the probe and the pump signals.

In optically amplified multi-span systems with several fiber segments in each span, each short segment may have different λ_0, and the total amplitude fluctuation at the receiver is the sum of XPM contributions created by each fiber segment. In this case, the normalized XPM frequency response can be expressed as

$$\Delta p_{jk}(\Omega, L_N) = \left| \sum_{n=1}^{N} \left\{ \gamma\, p_k^{(n)}(\Omega,0) \exp[-i\Omega d_{jk}^{(n-1)} L^{(n-1)}] \frac{\sin[\Omega^2 \sum_{m=n}^{N} \beta_2^{(m)} L^{(m)}/2] - \sin[\Omega^2 \sum_{m=n+1}^{N} \beta_2^{(m)} L^{(m)}/2] e^{-(\alpha - i\Omega d_{jk})L^{(n)}}}{\alpha - i\Omega d_{jk}^{(n)}} \right\} \right|^2 \qquad (2)$$

where, $L_N = \sum_{n=1}^{N} L^{(n)}$ is the total fiber length in the system with a total of N segments. $L^{(n)}$ and $\beta_2^{(n)}$ are fiber length and dispersion of the n-th segment with $L^{(0)} = 0$. $p_k^{(n)}(\Omega,0)$ is

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the pump channel input power spectrum into the *n-th* fiber segment and $d_{jk}^{(n)}$ is the relative walk-off between two channels in the *n-th* segment, with $d_{jk}^{(0)} = 0$. Equation (2) describes spectrum of the XPM induced intensity crosstalk in the probe channel normalized to its power level without crosstalk. Integrating this frequency spectrum over the receiver bandwidth, we get the normalized XPM crosstalk power which enters the receiver. In our statistical analysis, non-zero dispersion shifter fibers were used and a Gaussian distribution of λ_0 was assumed with the mean of 1515 nm and standard deviation of 3.52 nm.

Fig. 1 shows the statistical distribution of the normalized XPM crosstalk for a 2-channel, 5-span system with 100-km per span and a 0.8 nm channel spacing. The optical power launched into each fiber span is 8.5 dBm and the receiver electrical bandwidth is 7.5 GHz. In this case, increasing the number of segments (decreasing spool length) broadens the spreading of crosstalk levels, but the mean crosstalk level remains unchanged. However, with a wider channel spacing of 3.2 nm, the mean crosstalk level increases with the number of segments which is shown in Fig.2. We believe the reason for this increase is due to the phase discontinuity along the fiber. As a consequence, the XPM crosstalk from distant channels may not be as small as expected from uniform dispersion systems. Fig. 3 shows the 8 channel case with 0.8 nm channel spacing. The mean crosstalk level is significantly increased with larger number of segments.

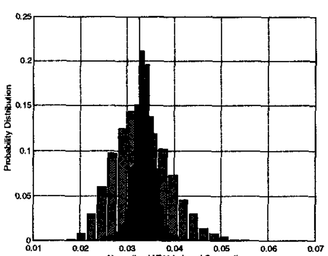

Fig. 1 5-span system, 2 channels with 0.8 nm **dark**: 1 segment per span **light**: 10 segments per span

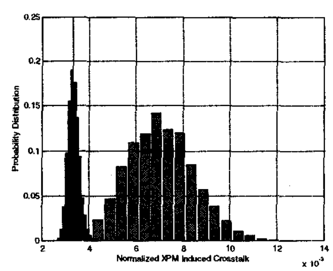

Fig. 2 5-span system, 2 channels with 3.2 nm **dark**: 1 segment per span **light**: 10 segments per span

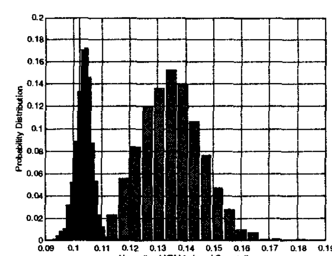

Fig. 3 5-span system, 8 channels with 0.8 nm **dark**: 1 segment per span **light**: 10 segments per span

In conclusion, statistic properties of XPM induced crosstalk in nonuniform-dispersion fiber links have been analyzed. Because of phase discontinuities along the fiber link, XPM induced crosstalk can be significantly higher than that evaluated from the system with a uniform dispersion map.

A systematic study on the impact of fiber random dispersion segmentation on the crosstalk levels has been conducted for different number of amplified fiber spans, different fiber types and different number of WDM channels. The results will be presented at the conference.

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References:

[1] R. Hui, Y. Wang, K. Demarest and C. Allen, to appear in *IEEE Photonics Technol. Lett.*, 1998.
[2] K. Inoue, *IEEE J. Lightwave Technol.*, Vol. 12, pp. 1023, 1994.