

Analysis of Cross-Polarization Modulation in Dispersion-Managed DWDM Systems

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Abstract—The impact of cross-polarization modulation in 10 Gb/s, 40 Gb/s, and mixed multi-span DWDM systems is compared using analytical methods which are based on a stochastic description of nonlinear polarization rotations.

I. INTRODUCTION

Cross-polarization modulation (XPoLM) is a consequence of nonlinearity-induced modulation of the fiber birefringence, which results in a rapid modulation of the state of polarization (SOP) of an optical signal as well as the PMD vector of the fiber. The SOP modulation is converted to amplitude fluctuations in the presence of polarization-dependent loss (PDL) or systems making use of polarization multiplex. The rapid modulation of the PMD vector severely degrades the efficiency of PMD compensation [1]. In the present work, a new method to predict the XPoLM-induced depolarization of an optical signal in DWDM systems is presented and used to estimate and compare the impact of XPoLM in systems operating at different channel bit rates.

II. MODELING XPoLM IN DWDM SYSTEMS

To model XPoLM in multi-channel systems, the optical signal in each channel is represented by a vector in Stokes space. The rapid motion of a probe channel's SOP due to linear fiber birefringence can be mathematically eliminated by using a suitable transformation of the coordinate system [2], thus isolating the nonlinear contributions to the SOP evolution. The instantaneous effect of XPoLM on the arrested SOP can then be described by a rotation around the sum $\mathbf{S}_\Sigma(z, t)$ of the Stokes vectors of all co-propagating channels [1], [3], [4]. This vector sum is a random quantity which consists of the sum of a large number of random vectors. The evolution of the SOPs is then modeled as a superposition of many random rotations: a Brownian motion, or diffusion, on the unit (Poincaré) sphere.

Such diffusions have been described in the past and their statistical properties, in particular the resulting distribution functions, are well known [5]. These properties depend, under the assumptions of mutual independence and uniform distribution of the individual Stokes vectors, only on the stochastic process $\mathbf{S}_\Sigma(z)$, which is defined by its distribution and covariance functions. According to the central limit theorem, its distribution will be approximately isotropic trivariate Gaussian. Its covariance function is defined as

$$C_{\Sigma\Sigma}(z_1, z_2) = E[\mathbf{S}_\Sigma(z_1) \cdot \mathbf{S}_\Sigma(z_2)] - E[\mathbf{S}_\Sigma(z_1)] E[\mathbf{S}_\Sigma(z_2)]$$

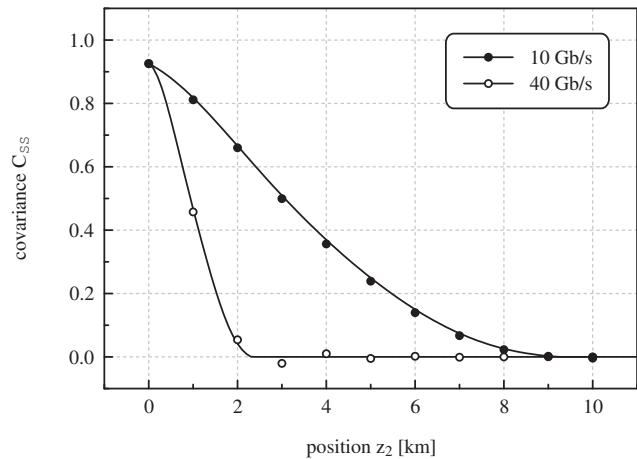


Fig. 1. Contribution of a single-channel to the covariance function $C_{\Sigma\Sigma}(0, z_2)$ for simplified theoretical model (lines) vs. full split-step / coarse-step model (symbols): 10 Gb/s and 40 Gb/s NRZ at 100 GHz frequency separation from reference frequency (probe); $D_{GVD} = 16$ ps/nm/km, $\alpha = 0.2$ dB/km, $\gamma = 1.31 \cdot 10^{-3}$ (Wm) $^{-1}$, $D_{PMD} = 0.5$ ps km $^{-1/2}$.

where $E[\cdot]$ is the statistical expectation, and can be approximated analytically in a straightforward manner by accounting for attenuation, initial pulse shape, channel walk-off, and SOP decorrelation due to PMD. Fig. 1 compares this analytical contribution to $C_{\Sigma\Sigma}(0, z_2)$ of a single channel to simulations using the split-step Fourier method with a coarse-step PMD model. The difference is insignificant. The compound covariance function for the WDM system is then the sum of the contributions of all channels. The distribution of the terminal SOPs will be symmetric around the initial SOP when the diffusion is isotropic, and can thus be given in terms of the displacement angle θ between them. The degree of polarization (DOP), which is often used to quantify the effects of XPoLM, is obtained from

$$DOP = E[\cos \theta] = \exp(-\kappa \sigma_\Sigma^2)$$

with

$$\sigma_\Sigma^2 = \int_0^L \int_0^L C_{\Sigma\Sigma}(z_1, z_2) dz_2 dz_1,$$

$\kappa = 1/3 (8\gamma/9)^2$ with fiber nonlinear parameter γ , and system

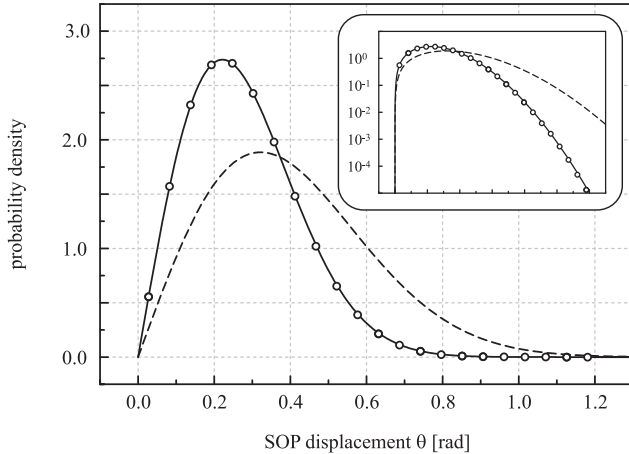


Fig. 2. Asymptotic (high channel load) probability density functions of the SOP displacement angle θ for DOP = 0.95 (solid lines) and DOP = 0.90 (dashed lines); symbols show Monte Carlo simulation results of a 21-channel 10 Gb/s system with $E[\text{DOP}] = 0.95$ for comparison; inset: logarithmic scale.

length L . Fig. 2 shows exemplary the SOP distribution in terms of θ for DOP values of 0.95 and 0.90; the tail of this distribution, in particular the probability $P(\theta > \pi/2)$ is of great interest in polarization multiplex systems, where it will directly affect the BER.

III. RESULTS

The covariance functions plotted in Fig. 1 show that σ_{Σ}^2 and thus the DOP reduction will be larger for 10 Gb/s than for 40 Gb/s systems, which is mainly due to the faster walk-off when the pulses are shorter. For the same reason, σ_{Σ}^2 decreases with increasing frequency spacing between channels. One may thus expect XPolM to play a minor role in 40 Gb/s systems. However, to maintain a comparable OSNR, 40 Gb/s channels are usually launched with $\approx 6\text{dB}$ higher power while the variance σ_{Σ}^2 scales with the square of the optical power. Therefore, higher-speed channels are expected to be also severely affected when maintaining high OSNR values.

These results are summarized in the plots of Fig. 3. In the 10 Gb/s \rightarrow 40 Gb/s migration scenarios, every second 10 Gb/s channel is replaced by a 40 Gb/s channel. Pure 10 Gb/s and 40 Gb/s systems are also shown for comparison. In all systems, the DOP of the central channel, corresponding to the channel which experiences the largest depolarization, is determined using the theory of Sec. II. All systems in Fig. 3 are modeled with full inline dispersion compensation and NRZ data modulation.

In [1], Karlsson found that an XPolM-related reduction of the DOP to below 0.97 results in a noticeable decrease in PMD compensation efficiency, while values below 0.90 may render compensation ineffective. Fig. 3 shows that such a situation may occur after only a few spans in pure and mixed 40 Gb/s systems if no precautions are taken to suppress XPolM.

Such precautions could consist of lower launch power; using fibers with high local GVD also reduces the distance over

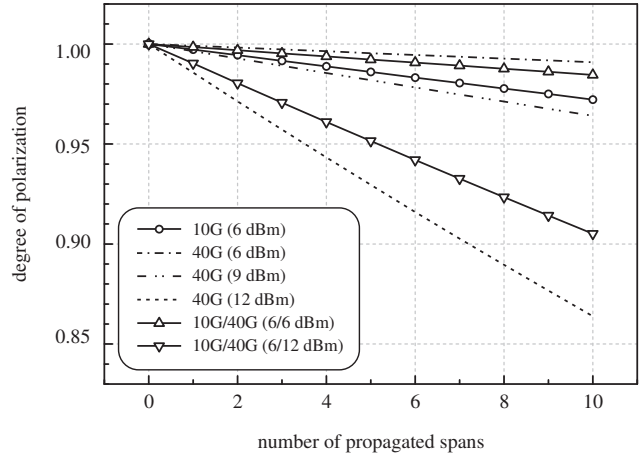


Fig. 3. DOP vs. propagated 100 km SSMF spans for a 21-channel NRZ DWDM system; channel separation $\Delta f = 100$ GHz, fiber is same as in Fig. 1. Accumulated GVD is fully compensated at the end of each span. Mixed rate systems have alternating 10/40 Gb/s allocation, with 40 Gb/s center (probe) channel.

which \mathbf{S}_{Σ} is significantly correlated within a span, thus reducing σ_{Σ}^2 and increasing the DOP. Sufficient residual dispersion per span decreases the correlation of \mathbf{S}_{Σ} between spans, while modern fibers with low PMD increase it. Reducing the frequency separation between channels, on the other hand, further aggravates XPolM. It should be noted that in most cases in which the DOP is significantly reduced by XPolM, the optical signals will also be severely degraded by SPM, XPM and FWM. In particular, the dependence of XPM distortions on various system parameters is closely related to that of XPolM.

IV. SUMMARY AND CONCLUSIONS

A new method to analytically model the SOP dispersion caused by XPolM in dispersion-managed DWDM systems as a diffusion process has been proposed. It allows to quickly compare the influence of a number of system parameters on the magnitude of XPolM effects, in particular the nonlinear depolarization of particular channels. By means of a typical system example it was shown that the effects can be considerable, also in 40 Gb/s systems; high local and average GVD and high fiber PMD reduce the XPolM effects.

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