Comparison of XPM and XpolM-Induced Impairments in Mixed 10G – 100G Transmission

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1. INTRODUCTION

The deployment of 100G channels over legacy 10 and 40G infrastructure started in late 2009 and has been continuously accelerating so far. Since accumulated chromatic dispersion and linear polarization effects (PMD and polarization cross-talk between orthogonal channels) are compensated using digital signal processing (DSP), the performance of the 100G channels is mainly limited by optical noise, tight optical filtering (due to cascaded ROADMs) and fiber nonlinearities including intra-channel (SPM, iXPM, iFWM) and inter-channel (XPM, XpolM) effects. The latter effects may require to switch-off neighboring legacy channels to operate the 100G channel and are therefore of great interest. In the following, we intend to understand whether XpolM-induced depolarization or XPM-induced timing jitter represents the main impairment for the transmission of a 112 Gb/s DP-QPSK signal over 800 km of legacy 10G system. FWM effects can be ignored in this scenario as the phase-matching condition requires very low channel spacing in standard single mode fibers (G652).

2. XpolM and XPM

Cross-polarization modulation (XpolM) is an inter-channel effect resulting in fast polarization-modulation of signals and therefore to a depolarization of the transmitted signal, resulting in fading and channel cross-talk for dual-polarization (DP) signals. Looking at a particular channel (*probe*) XpolM-induced depolarization depends on the variance of the Stokes vector of the aggregate co-propagating channels (*pump*). Expressed in Stokes space [1,2], the variation of the probe signal state of polarization (SOP) described by its Stokes vector , $\vec{s}$ is given by:

$$\frac{\partial \vec{s}}{\partial z} = \frac{8}{9}\gamma \vec{s}_T \times \vec{s} \tag{1}$$

$\vec{s}_T$ being the Stokes vector of the aggregated probe and pump signals. Note that (1) can be written as $\vec{s}/\partial z \approx 8/9\,\gamma \vec{p} \times \vec{s}$ when the power of the pump is much larger than the one of the probe signal, i.e. XpolM effects lead to a rotation of the probe channel Stokes vector around the one of the pump.

In order to illustrate the impact of XpolM, the probe SOP evolution over the transmission line is displayed in Figure 1 assuming a CW pump and probe. For sake of simplicity, a loss- and dispersion-less fiber with constant birefringence has been considered so that the SOP of the probe and pump remain constant over the transmission line (in linear regime). The results are reported for different pump SOPs. When the launched SOPs of the probe and pump are identical (or orthogonal) no polarization modulation takes place.

Figure 1. Evolution of the probe SOP along the transmission line (green circles) for different launch SOPs of probe (A) and pump (B).

The fact that the state of polarization of the probe and pump evolve randomly over the transmission due to CD and PMD makes the XpolM effect pattern-depended and stochastic. The resulting penalty has been predicted to be particularly important for dual-polarization (DP) signals deployed over legacy dispersion managed 10 Gb/s systems [3].

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3. THEORETICAL ANALYSIS

In order to distinguish XPM and XpolM effects, we reformulate the Manakov equation [4] which governs the propagation of an optical signal in randomly varying birefringence fiber:

$$\left[\frac{\partial}{\partial z}+\frac{\alpha}{2}-j\frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2}+\beta_1\frac{\partial}{\partial t}\right]U=-j\frac{8}{9}\gamma|U|^2\,U \quad (2)$$

U is a complex vector describing the envelope of the optical field propagating on the local fast and slow polarization axes of the fiber. Writing **U** = **S** + **P**, where **S** and **P** stand for the signal of interest (probe) and the pump, respectively, and assuming that **S** and **P** propagate on different frequencies, the equation describing the propagation of **S** can be derived from (2):

$$\left[\frac{\partial}{\partial z}+\frac{\alpha}{2}-j\frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2}+\beta_1\frac{\partial}{\partial t}\right]S=-j\frac{8}{9}\gamma([|S|^2\ +|P|^2\,]S+(P^*.S)P) \quad (3)$$

where * stands for complex conjugation and **.** for the inner scalar product. Noting that $(\boldsymbol{P}^*.\boldsymbol{S})\boldsymbol{P}=(\boldsymbol{P}.\boldsymbol{P}^*).\boldsymbol{S}$ and $(\boldsymbol{P}.\boldsymbol{P}^*)=\frac{1}{2}\left(\boldsymbol{P}^*.\boldsymbol{P}+\widehat{\boldsymbol{P}}\vec{\boldsymbol{\sigma}}\right)$ [5], $\widehat{\boldsymbol{P}}$ being the Stokes vector of the pump and $\vec{\boldsymbol{\sigma}}$ the Pauli spin vector in Stokes space, equation (3) becomes [1,2]:

$$\left[\frac{\partial}{\partial z}+\frac{\alpha}{2}-j\frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2}+\beta_1\frac{\partial}{\partial t}\right]S=-j\frac{8}{9}\gamma\left[|S|^2\ +\frac{3}{2}|P|^2+\frac{1}{2}|P|^2\hat{p}\vec{\sigma}\ \right]S \quad (4)$$

where $\widehat{\boldsymbol{p}}$ is the normalized Stokes vector of the pump ($\widehat{\boldsymbol{P}}=|\boldsymbol{P}|^2\widehat{\boldsymbol{p}}$). The first nonlinear terms are polarization independent and describe the effects of SPM and XPM whereas the last term depends on the relative polarization states of the pump and probe signal. In the literature (see [1], [6]) this last term is often referred to as XpolM. However, this last term also contains polarization dependent XPM and therefore does not always lead to depolarization. This is obvious for the case where the pump SOP is aligned or orthogonal to the one of the signal $j\frac{8}{9}\gamma\frac{1}{2}|\boldsymbol{P}|^2\widehat{\boldsymbol{p}}\vec{\boldsymbol{\sigma}}\boldsymbol{S}=\mp j\frac{8}{9}\gamma\ \frac{1}{2}|\boldsymbol{P}|^2\boldsymbol{S}$ which affects the phase of both polarizations of $\boldsymbol{S}$ equally, and thus does not modulate the signal polarization.

To illustrate this point, we express the pump signal as a sum of two signals with aligned or orthogonal SOP with regard to the probe signal. Replacing $\boldsymbol{P}$ by $\boldsymbol{P}_{\parallel s}+\boldsymbol{P}_{\perp s}$ in (3), it comes:

$$\left[j\frac{\partial}{\partial z}+\frac{\alpha}{2}-j\frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2}+\beta_1\frac{\partial}{\partial t}\right]\boldsymbol{S}=-j\frac{8}{9}\gamma\left(\left[|\boldsymbol{S}|^2\ +|\boldsymbol{P}|^2+\left|\boldsymbol{P}_{\parallel s}\right|^2\right]\boldsymbol{S}+\left(\boldsymbol{P}_{\parallel s}^*.\boldsymbol{S}\right)\ .\boldsymbol{P}_{\perp s}\right) \quad (5)$$

The first nonlinear term is affecting only the phase of $\boldsymbol{S}$ whereas the second is pointing in the orthogonal direction ($\boldsymbol{P}_{\perp s}$) and therefore describes the XpolM effect. The magnitude of the XPM and XPolM terms as defined in (5) are reported versus the ratio $\left|\boldsymbol{P}_{\perp s}\right|^2/|\boldsymbol{P}|^2$ in Figure 2. It can be observed that depolarization is zero when the SOP of the pump is aligned ($\left|\boldsymbol{P}_{\perp s}\right|^2=\boldsymbol{0}$) or orthogonal ($\left|\boldsymbol{P}_{\parallel s}\right|^2=\boldsymbol{0}$) with the signal SOP and is maximum for $\left|\boldsymbol{P}_{\parallel s}\right|^2=\left|\boldsymbol{P}_{\perp s}\right|^2$. Note that the definition of the XpolM effect as reported in (4) corresponds to this worst case.

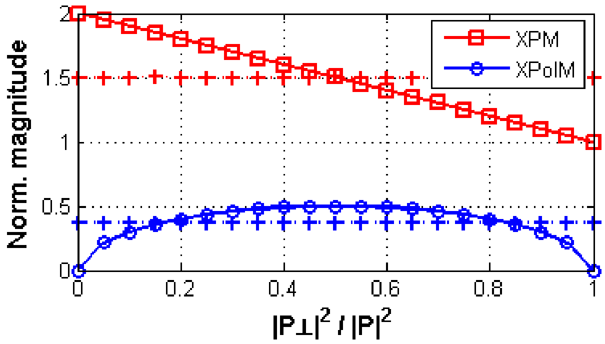

Figure 2. Normalized magnitude of the XPM and XpolM terms as defined in (5). The + stand for the mean magnitude (averaged over the Poincare sphere).

4. INVESTIGATED SYSTEM

The transmission of a 112Gb/s DP-QPSK at 1550 nm together with six 10Gb/s RZ neighboring channels at 100 GHz channel spacing over a optical dispersion managed (ODM) transmission line with up to 20 spans is simulated using *VPItransmissionMaker 8.6*. Each span consists of 80 km of G652 fiber, an ideal (linear) dispersion compensating module (DCM) and an EDFA compensating exactly for the loss of the transmission fiber and DCM. 1% residual dispersion per span is considered. Residual dispersion and linear polarization effects (PMD, SOP rotation) are compensated ideally in front of the receiver by inverting the linear Jones matrix of the transmission line in order to focus on XPM and XpolM effects only. The performance of the DP-QPSK channel is reported by means of the required OSNR to achieve a BER of 1e-3, estimated using error-counting. Since optical noise is added in front of the receiver, nonlinear signal-noise interactions are ignored in this investigation.

Single-channel performance

The single channel system has first been considered in order to estimate the impact of intra-channel nonlinearities. The system performance (required OSNR) as well as the achievable OSNR (assuming 10 dB loss per DCM and 5 dB EDFA noise figure) are reported for varying input powers in Figure 3. Results show that intra-channel nonlinearities are weakly-dependent on PMD and that a maximum power margin of 7 dB is available at 2 dBm input power (required OSNR for back-to-back = 14 dB). After subtracting 4 dB power margin for aging and system design inaccuracies, 3dB power margin could be allocated to inter-channel nonlinear penalties.

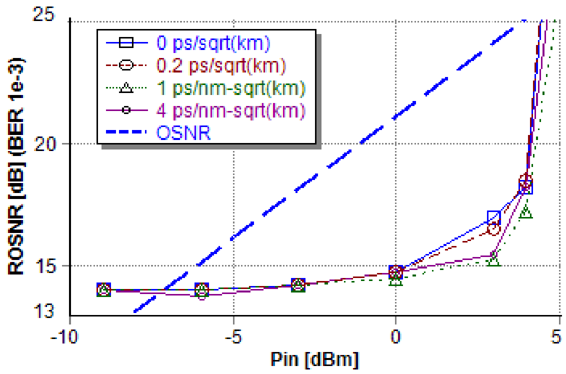

Figure 3. Required OSNR (for BER = 1e-3) vs. input power for the 112Gb/s DP-QPSK channel in single-channel configuration.

WDM performance

In the WDM configuration, the power of the 100G channel has been set to -9dBm while the power of the 10G channels has been varied between -6 and 6dBm in order to focus on the impact of XPM and XpolM only. The SOPs of the 10G channels have been set to vary randomly or be aligned with one tributary (x-channel) of the DP-QPSK signal. According to (5) and assuming that the relative SOPs of the pump and signal remain constant along the transmission line (2[nd] order PMD is neglected), no XpolM effect takes place in the latter case. Additionally, the x-tributary experiences a stronger XPM-effect than the y-tributary (see Figure 2). On the contrary, when the SOP of the pump is randomly varying x and y-tributaries experience similar XPM and XpolM effects.

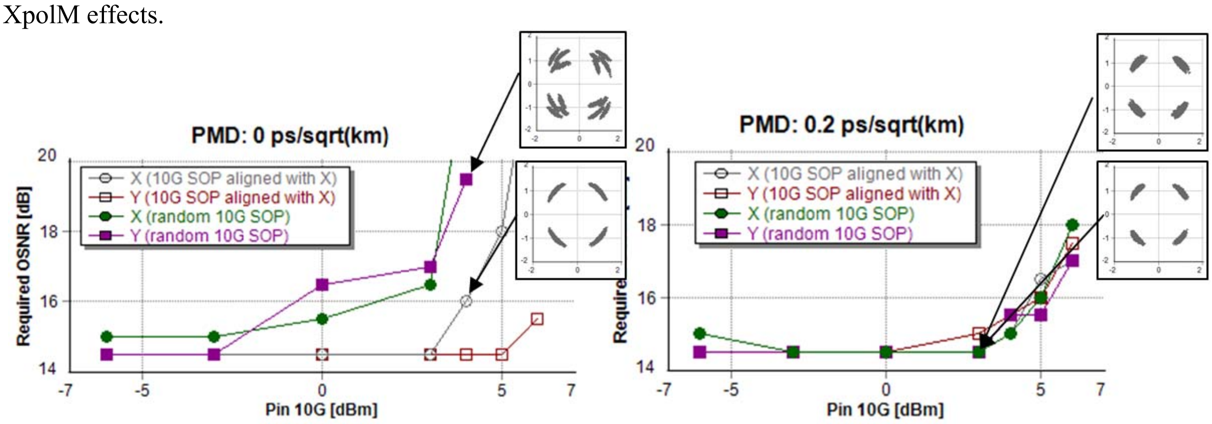

Figure 4. Required OSNR for the x and y-tributaries of the 100G DP-QPSK channel vs. 10G channels input power for different launch SOPs of the 10G channels and fiber PMD coefficient. Insert: ASE-free constellation diagrams with polarized (top, aligned with x tributary) or depolarized (bottom) 10G channels (3dBm input power).

The results reported in Figure 4 show that XpolM ("*random 10G SOP*") leads to large additional penalties when PMD is neglected in the fiber, but that its impact is strongly reduced for standard PMD values. Since XpolM effect depends on the SOP of the aggregate 10G channels (pump), which is affected by the fiber local birefringence, each configuration has been simulated 50 times with different fiber birefringence profiles and varying starting SOP of the pump (both polarized and depolarized 10G channels pump have been considered). The required OSNR for the 100G channel is reported versus the signal depolarization (generated by XpolM) in Figure 5 for systems with 3dBm input power for the 10G channels.

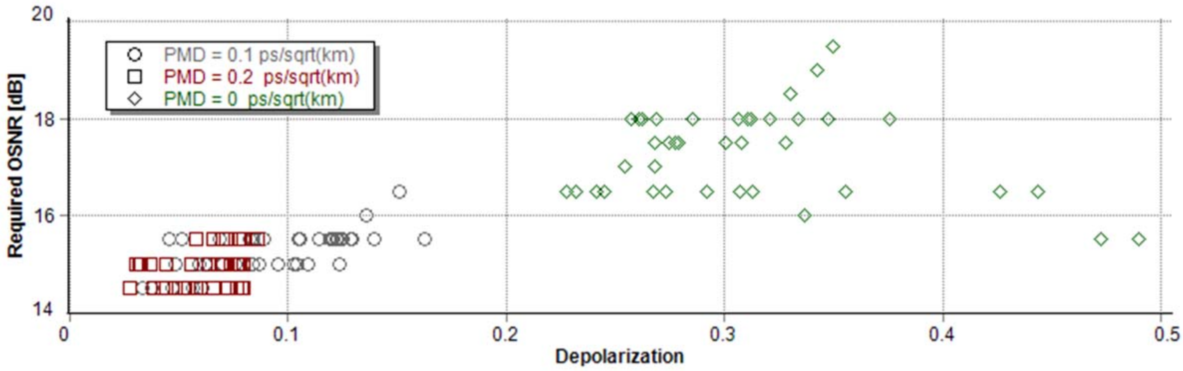

Figure 5. Required OSNR vs. depolarization for 50 different birefringence profiles of the transmission line with 0, 0.1 and 0.2 ps/$\sqrt{km}$ PMD (Pin of 10G channels =3 dBm).

The signal depolarization is defined as $\langle|\Delta\hat{\boldsymbol{S}}|\rangle/|\boldsymbol{S}|^2$ where $\Delta\hat{\boldsymbol{S}}$ is the variation of the signal SOP (with respect to its original value) measured in the middle of a DP-QPSK symbol. Results show that the correlation between depolarization and required OSNR is very low for systems with non-zero PMD, and therefore that XpolM-induced channel cross-talk is negligible compared to XPM-induced distortions in such systems.

5. CONCLUSION

We reviewed the origin and impact of the cross polarization modulation (XpolM) effect. An analysis of the Manakov equation has been carried out in order to differentiate between XpolM and XPM effects. Based on this analysis, it has been argued that the impact of XpolM may have been overestimated so far. To verify this statement, the performance of a 112Gb/s DP-QPSK channel over 10Gb/s legacy system has been investigated with the help of numerical simulations. We showed that the impact of XpolM is smaller than the impact of XPM and intra-channel nonlinearities (iXPM, iFWM). Our presented results assessing the impact of the XpolM effect confirmed theoretical predictions that have been reported in [7]. Finally, our investigations have shown that the impact of XpolM–induced distortion is reduced by PMD.

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