Polarization scattering by intra-channel collisions

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Abstract: We show that polarization modulated and polarization multiplexed transmission may be significantly impaired by the polarization scattering induced by intra-channel cross-phase modulation and four-wave mixing. In polarization multiplexed transmission, channel interleaving may be used to mitigate the effect when two-pulse collisions are dominant.

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1. Introduction

It is well known that intra-channel cross-phase modulation (XPM) may produce significant polarization scattering in soliton transmission [1]. Intra-channel XPM is however a significant process in highly dispersed pulse transmission, so that we may expect a similar polarization scattering to occur in polarization multiplexed or polarization modulated highly dispersed pulse transmission even if the transmission is single channel. This effect may impair high baud rate single channel transmission like it impaired multi-channel soliton transmission. Using a perturbation approach [2], we analyze in this Letter the effect of intra-channel collisions in polarization modulated or polarization multiplexed systems, and show that they may indeed induce signal depolarization similar to that caused by collisions between wavelength division multiplexed solitons [1]. Simple analytical expressions capturing the essence of the phenomenon and quantitatively predicting the observed amount of depolarization are derived. We finally show that a relative delay of the two multiplexed channels by half of a symbol duration (channel interleaving) reduces the scattering by more than one order of magnitude.

2. First order perturbation theory

For moderate amounts of polarization mode dispersion (PMD), the evolution of the vector electric field **E** of a polarized optical field in a nonlinear dispersive fiber, averaged over the fast

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polarization evolution, is well described by the Manakov equation [1, 3]

$$\frac{\partial \mathbf{E}}{\partial z} = -i\frac{\beta''}{2}\frac{\partial^2 \mathbf{E}}{\partial t^2} + i\frac{8}{9}\gamma f(z)\left(\mathbf{E}^\dagger \mathbf{E}\right)\mathbf{E}. \tag{1}$$

Here, β'' is the group velocity dispersion (negative in the anomalous dispersion region), $\gamma = 2\pi n_2/(\lambda A_{\rm eff})$ is the fiber nonlinear coefficient, n_2 is the nonlinear refractive index, and $A_{\rm eff}$ is the effective area of the fiber. The function $f(z)$ rescales the fiber nonlinearity to include the effect of a non-uniform power profile caused by the fiber loss. When equally spaced lumped Erbium amplifiers are used, this function is $f(z) = \exp[-\alpha\,\mathrm{mod}(z, z_s)]$, where mod is the modulus function, α is the power attenuation coefficient, and z_s is the span length. Let us now assume that the field $\mathbf{E} = \sum_n \mathbf{E}_n(z,t)$ is a sequence of well separated pulses $\mathbf{E}_n$ centered at $T_n = nT$, with T the symbol duration, and that the message is encoded by a different polarization, phase and amplitude of the individual pulses. A large dispersion adds on pulses a strong time-frequency correlation, because each frequency component is delayed proportionally to its detuning from the center frequency. Consequently, it is possible to show that the well-known selection rules of four-wave mixing in frequency reflect into similar rules in time domain. As a result of these rules, the evolution of the pulse centered at $T_0 = 0$ is described by the equation

$$\frac{\partial \mathbf{E}_0}{\partial z} = -i\frac{\beta''}{2}\frac{\partial^2 \mathbf{E}_0}{\partial t^2} + i\frac{8}{9}\gamma f(z)\sum_{k=j+l,j,l}\mathbf{E}_k^\dagger \mathbf{E}_j \mathbf{E}_l, \tag{2}$$

where the triple sum in Eq. (2) is extended to terms where the four-wave mixing interaction is resonant with the pulse $\mathbf{E}_0$, which are those with $T_k = T_j + T_l$ hence $k = j + l$. In a three dimensional space (the Stokes space) spanned by the unit vectors $(\vec{e}_1, \vec{e}_2, \vec{e}_3)$, let us now introduce the Pauli spin vector as $\vec{\sigma} = (|x\rangle\langle x| - |y\rangle\langle y|)\,\vec{e}_1 + (|y\rangle\langle x| + |x\rangle\langle y|)\,\vec{e}_2 + i\,(|y\rangle\langle x| - |x\rangle\langle y|)\,\vec{e}_3$, where $|x\rangle$ and $|y\rangle$ are unit polarization vectors parallel to the x and y axis respectively. Let us then define $\mathbf{E}_n = E_n|s\rangle$ where $|s\rangle$ is the unit polarization state, and the Stokes vectors of the field is $\vec{s} = \langle s|\vec{\sigma}|s\rangle$. After multiplying by $\mathbf{E}_0^\dagger\vec{\sigma}$ both sides of Eq. (2), adding the hermitian conjugate, and integrating over t we obtain

$$\frac{\mathrm{d}}{\mathrm{dz}}\left[\int \mathrm{d}t|E_0|^2\vec{s}_0(z,t)\right] = \int \mathrm{d}t\,2\mathrm{Re}\left[-i\frac{\beta''}{2}\mathbf{E}_0^\dagger\vec{\sigma}\frac{\partial^2\mathbf{E}_0}{\partial t^2} + i\frac{8}{9}\gamma f(z)\sum_{j,l}\left(\mathbf{E}_0^\dagger\vec{\sigma}\mathbf{E}_l\right)\left(\mathbf{E}_{j+l}^\dagger\mathbf{E}_j\right)\right]. \tag{3}$$

An integration by parts $-i\int \mathrm{d}t\mathbf{E}_0^\dagger\vec{\sigma}(\partial_t^2\mathbf{E}_0) = i\int \mathrm{d}t(\partial_t\mathbf{E}_0^\dagger)\vec{\sigma}(\partial_t\mathbf{E}_0)$ shows that the term proportional to dispersion is purely imaginary so that it cancels at the right hand side, so that

$$\frac{\mathrm{d}}{\mathrm{dz}}\left[\int \mathrm{d}t|E_0|^2\vec{s}_0(z,t)\right] = \frac{8}{9}\gamma f(z)\int \mathrm{d}t\,\mathrm{Re}\left[2i\sum_{j,l}E_0^*E_{j+l}^*E_lE_j\,\langle s_0|\vec{\sigma}|s_l\rangle\langle s_{j+l}|s_j\rangle\right]. \tag{4}$$

If we define the average polarization across the pulse as $\vec{s}_0(z) = \int \mathrm{d}t|E_0|^2\vec{s}_0(z,t)/U_0$, where $U_0 = \int \mathrm{d}t|E_0|^2$ is the total energy of the pulse centered at $T_0 = 0$, we obtain

$$\frac{\mathrm{d}\vec{s}_0(z)}{\mathrm{dz}} + \vec{s}_0\frac{\mathrm{d}\ln U_0(z)}{\mathrm{dz}} = \frac{8}{9}\gamma f(z)\mathrm{Re}\left[2i\sum_{j,l}\left(\frac{1}{U_0}\int \mathrm{d}tE_0^*E_{j+l}^*E_lE_j\langle s_0|\vec{\sigma}|s_l\rangle\langle s_{j+l}|s_j\rangle\right)\right]. \tag{5}$$

Equation (5) may be solved using a perturbation approach, by entering at right hand side for E_n, $n = 0, k, l, j$ and $|s_n\rangle$, their expressions in the absence of nonlinearity. To this purpose, let us assume that the input pulses have a well-defined polarization, uniform across the pulses, that is $\mathbf{E}_n(z=0,t) = E_n(0,t)|s\rangle$, where the unit polarization vector $|s\rangle$ is independent of t. A

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purely dispersive propagation preserves the uniformity of the polarization hence, within the perturbation approach, $\langle s_0|\vec{\sigma}|s_l\rangle\langle s_{j+l}|s_j\rangle$ at right hand side of Eq. (5) may be assumed as time independent quantities, and pulled out of the integral.

It is interesting to consider the limit case of two-pulse interaction, in which two pulses of the four at right hand side of Eq. (5) overlap, that is the particular case $j = 0$. Using that $|s_l\rangle\langle s_l| = \frac{1}{2}(1+\hat{s}_l\cdot\vec{\sigma})$ and $i[\vec{\sigma}(\vec{\sigma}\cdot\vec{s}_l) - (\vec{\sigma}\cdot\vec{s}_l)\vec{\sigma}]/2 = \vec{s}_l\times\vec{\sigma}$ [4], we obtain from Eq. (5)

$$\frac{\mathrm{d}\vec{s}_0(z)}{\mathrm{dz}} + \vec{s}_0\frac{\mathrm{d}\ln U_0(z)}{\mathrm{dz}} = \frac{8}{9}\gamma f(z)\sum_l\left(\frac{1}{U_0}\int \mathrm{d}t|E_l|^2|E_0|^2\right)\vec{s}_l\times\vec{s}_0. \tag{6}$$

In the special case of Gaussian pulses $E_n(0,t) = A_n\exp[-t_n^2/(2\tau^2)]$ where $t_n = t - nT$, the solution in the absence of nonlinearity may be analytically expressed as $E_n(z,t) = A_n\exp\left(-t_n^2/\{2\tau^2[1+\rho(z)]\}\right)/\sqrt{1+\rho(z)}$, where $\rho(z) = -i(|\beta''|/\beta'')(z-z^*)/z_d$. Here, we defined the dispersion length $z_d = |\beta''|/\tau^2$, and we included a possible pre-dispersion of the pulses of the amount $\beta_{\mathrm{pre}} = -\beta''z^*$, in ps^2 if β'' is in ps^2/km and z^* in km. For Gaussian pulses, Eqs. (5) and (6) become

$$\frac{\mathrm{d}\vec{s}_0(z)}{\mathrm{dz}} + \vec{s}_0\frac{\mathrm{d}\ln U_0}{\mathrm{dz}} = \frac{8}{9}\gamma f(z)\sqrt{2}\pi\tau^2\sum_{j,l}\frac{A_{j+l}A_lA_j}{A_0}\mathrm{Re}\left[2iG(T_l,T_j,z)\langle s_0|\vec{\sigma}|s_l\rangle\langle s_{j+l}|s_j\rangle\right], \tag{7}$$

$$\frac{\mathrm{d}\vec{s}_0(z)}{\mathrm{dz}} + \vec{s}_0\frac{\mathrm{d}\ln U_0}{\mathrm{dz}} = \frac{8}{9}\gamma f(z)\sqrt{2}\pi\tau^2\sum_l A_l^2G(lT,0,z)\vec{s}_l\times\vec{s}_0, \tag{8}$$

where we defined the normalized bivariate normal distribution, albeit with an imaginary correlation coefficient $\rho(z) = -i(|\beta''|/\beta'')(z-z^*)/z_d$, as

$$G(T_1,T_2;z) = \frac{1}{2\pi\tau^2\sqrt{1-\rho^2(z)}}\exp\left\{-\frac{T_1^2+T_2^2+2\rho(z)\,T_1T_2}{2\tau^2[1-\rho^2(z)]}\right\}. \tag{9}$$

The case of two-pulse interaction described by Eqs. (6) and (8) corresponds to pure XPM. In this case, the component parallel to $\vec{s}_0$ at the right hand side of Eqs. (6) and (8) is zero, hence $\mathrm{d}\ln U_0/\mathrm{dz} = 0$. This means that two-pulse collisions does not produce exchange of energy between the two pulses but only a change in their polarization. In addition, there is no polarization scattering if the pulses are either co-polarized ($\vec{s}_0$ parallel to $\vec{s}_l$) or cross-polarized ($\vec{s}_0$ anti-parallel to $\vec{s}_l$). Note once again the strong analogy between the two-pulse case and the polarization scattering caused by inter-channel XPM in wavelength division multiplexed and polarization multiplexed soliton transmission [1].

Four pulse interactions described by Eqs. (5) and (7) with $j \neq 0$, on the other hand, correspond to non-degenerate intra-channel four-wave mixing. In this case, intra-pulse power transfer may take place. This is reflected by the fact that $\langle s_0|\vec{\sigma}|s_l\rangle$ may have a component parallel to $\vec{s}_0$. Furthermore, polarization scattering may also occur between three co-polarized pulses and one cross-polarized. To see this, let us assume without loss of generality that $\vec{s}_0 = \vec{e}_2$. In this case, in Eqs. (5) or (7) the rate of power change $\mathrm{d}\ln U_0(z)/\mathrm{dz}$ is proportional to $|\langle s_0|\vec{\sigma}|s_l\rangle\cdot\vec{e}_2|^2 = (1+\vec{s}_l\cdot\vec{s}_0)/2$, whereas the rate of depolarization $\mathrm{d}\vec{s}_0/\mathrm{dz}$ have components along $\vec{e}_1$ and $\vec{e}_3$ proportional to $|\langle s_0|\vec{\sigma}|s_l\rangle\cdot\vec{e}_{1,3}|^2 = (1-\vec{s}_l\cdot\vec{s}_0)/2$. Therefore, when $\vec{s}_l\cdot\vec{s}_0 = -1$, hence when the pulses at l and 0 are orthogonally polarized, $\mathrm{d}\vec{s}_0/\mathrm{dz}$ may have non-zero depolarizing components parallel to $\vec{e}_1$ and $\vec{e}_3$ if the pulse at j is co-polarized with the pulse at $j+l$ so that $|\langle s_{j+l}|s_j\rangle| = 1$.

3. Numerical example: polarization multiplexed QPSK signal

Let us now evaluate the variance of the polarization spread in a polarization-multiplexed quadrature phase shift keying (QPSK) signal, where all pulses have the same amplitude $A_k = A$

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and the phases of the pulses on each polarization are 0, $\pi/2$, π and $3\pi/2$, assuming synchronous pulse streams on the two polarizations. To evaluate the effect of two-pulse collisions, we notice that in this case the possible pulse polarizations are the two linear polarizations $\vec{s} = (0, \pm 1, 0)$ and the two circular polarizations $\vec{s} = (0, 0, \pm 1)$. Let us assume that the pulse at $T_0 = 0$ has the linear polarization $\vec{s}_0 = (0, 1, 0)$. The interacting pulses will be with equal probability linearly polarized, in which case $\vec{s}_0(0) \times \vec{s}_l(0) = 0$, or circularly polarized, in which case $\vec{s}_0(0) \times \vec{s}_l(0) = (\pm 1, 0, 0)$. Assuming a random message, the polarization spread $\Delta\vec{s}_0 = \vec{s}_0(z) - \vec{s}_0(0)$ is on average zero, $\langle \Delta\vec{s}_0 \rangle = 0$, whereas its variance along $\vec{e}_1$ is

$$\langle [\Delta\vec{s}_0(z) \cdot \vec{e}_1]^2 \rangle_{2-\mathrm{pulse}} = \left(\frac{8}{9} \gamma \pi A^2 \tau^2 \right)^2 \sum_{l \neq 0} \left[\int_0^z \mathrm{d}z' \, f(z') G(lT, 0, z') \right]^2, \tag{10}$$

where the sum is over all pulses that overlap with the pulse 0 during propagation up to z. Notice that, if the number of interacting pulses is large, because of the central limit theorem $\Delta\vec{s}_0 \cdot \vec{e}_1$ is Gaussian distributed with zero average and variance given by Eq. (10).

The estimate of the polarization scattering caused by multiple pulse collisions requires the knowledge of the polarization and the absolute phase of the 16 transmitted pulses. They are in our example $\pm|\pm s_2\rangle$, $\pm|s_\pm\rangle$, $\pm i|\pm s_2\rangle$, and $\pm i|s_\pm\rangle$, where $|\pm s_2\rangle = (|x\rangle \pm |y\rangle)/\sqrt{2}$, $|s_\pm\rangle = (|x\rangle \pm i|y\rangle)/\sqrt{2}$. Assume that $|s_0\rangle = |+s_2\rangle$. We have $\langle s_2|\vec{\sigma}|s_2\rangle = \vec{e}_2$, $\langle s_2|\vec{\sigma}|-s_2\rangle = \vec{e}_1 + i\vec{e}_3$, $\langle s_2|\vec{\sigma}|s_+\rangle = (1-i)\vec{e}_1/2 + (1+i)(\vec{e}_2+\vec{e}_3)/2$, $\langle s_2|\vec{\sigma}|s_-\rangle = (1+i)\vec{e}_1/2 + (1-i)(\vec{e}_2-\vec{e}_3)/2$, and $\langle s_2|s_\pm\rangle = (1 \pm i)/2$ $\langle -s_2|s_\pm\rangle = (1 \mp i)/2$, $\langle s_2|-s_2\rangle = \langle s_+|s_-\rangle = 0$.

When the interaction is with a pulse l circularly polarized or co-polarized with the pulse in 0, the four wave mixing interaction has a component parallel to $\vec{s}_0$, which produces a change of the pulse energy U_0. This means that only the intra-channel two-pulse interaction is a real soliton-like collision, where there is no power transfer between the two pulses but only a polarization change. Four-pulse interaction (not unexpectedly) produces a polarization rotation of the pulse at 0 together with a phase dependent and polarization dependent power variation.

Notice that the average of $\langle s_{j+l}|s_j\rangle$ over all pulse is zero, so that the average polarization displacement is also zero. Squaring the expression for $\Delta\vec{s}_0(z) \cdot \vec{e}_{1,3}$, we obtain a four-fold sum of terms proportional to product of the real part of $a_1 = \langle s_0|\vec{\sigma}|s_l\rangle\langle s_{j+l}|s_j\rangle$ and $a_2 = \langle s_0|\vec{\sigma}|s_{l'}\rangle\langle s_{j'+l'}|s'_j\rangle$. Let us now use the expansion $\langle \mathrm{Re}(a_1)\mathrm{Re}(a_2)\rangle = 1/2[\langle \mathrm{Re}(a_1 a_2)\rangle + \mathrm{Re}(a_1 a_2^*)\rangle]$. The first term is zero for the phase symmetry of the channel. The second term is the real part of $\langle s_0|\vec{\sigma}|s_l\rangle\langle s_{j+l}|s_j\rangle \cdot \langle s_{j'}|s_{j'+l'}\rangle\langle s_{l'}|\vec{\sigma}|s_0\rangle$, which for isotropic polarization distribution has non-zero average only if $j = j'$ and $l = l'$. Using now that $\langle |\langle s_{j+l}|s_j\rangle|^2\rangle = 1/2$ and $\langle |\langle s_0|\sigma_{1,3}|s_l\rangle|^2\rangle = 1/2$, and the statistical independence of the two terms, we obtain $\langle \mathrm{Re}\left[2iG\langle s_0|\sigma_{1,3}|s_l\rangle\langle s_{j+l}|s_j\rangle\right] \mathrm{Re}\left[2iG\langle s_0|\sigma_{1,3}|s_{l'}\rangle\langle s_{j'+l'}|s_{j'}\rangle\right]\rangle = \delta_{j,j'}\delta_{l,l'}|G|^2/2$. Notice that, being the polarization of the pulse at 0 parallel to $\vec{e}_2$, depolarization of this pulse is caused by the fluctuations of the first and third component of the Stokes vector only.

The contribution of the four pulse collision to the polarization spread along $\vec{e}_1$ and $\vec{e}_3$ is the sum of the average squared of the individual elements of the sum, that is

$$\langle [\Delta\vec{s}_0(z) \cdot \vec{e}_{1,3}]^2 \rangle_{4-\mathrm{pulse}} = \left(\frac{8}{9} \gamma \pi A^2 \tau^2 \right)^2 \sum_{k=j+l, j \neq 0, l \neq 0} \left| \int_0^z \mathrm{d}z' \, f(z') G(T_l, T_j, z') \right|^2. \tag{11}$$

For the first component of $\vec{s}_0$, to this term should be added the one deriving from two-pulse collisions. The term with $j = 0$ has been excluded because it comes from two-pulse collisions, the term $l = 0$ has been excluded because it is zero at the right side of Eq. (7).

In Fig. 1 we show the depolarization of the pulse Stokes vectors on the Poincaré sphere in a transmission systems employing two polarization multiplexed QPSK signals at 50 Gbaud/s (200 Gbit/s aggregate rate). The pulses have a 5 ps full-width at half maximum Gaussian profile.

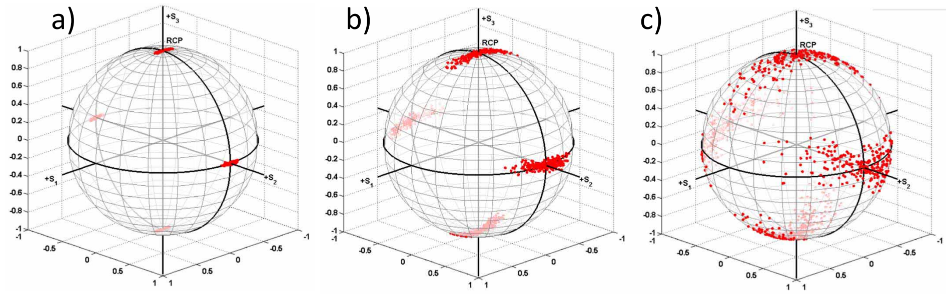

Fig. 1. Depolarization on the Poincaré sphere when two-pulse collisions are dominant, for 3 dBm (plot a), 7 dBm (plot b) and 13 dBm (plot c) average input power (per polarization).

The system is made of 7 spans of $z_s = 100$ km each hence total length $L = 700$ km, with pre-compensation $-\beta'' z^*$, full compensation after each span, and post-compensation at the receiver $-\beta''(z_s - z^*)$ so that 100% of the total fiber dispersion is compensated. Figure 2 has been obtained with no pre-compensation, $z^* = 0$. The fiber dispersion is 16 ps/nm/km, loss is 0.25 dB/km, and nonlinear coefficient $\gamma = 1.3$ W^{-1} km^{-1}. The average input power is (left to right) 3, 7 and 13 dBm. The polarization rotation caused by intra-channel collisions is evident.

Let us now make a quantitative comparison between theory and simulations, for the same system analyzed in Fig. 1. In Fig. 2a we show the standard deviation of the first component of the Stokes vector, $\langle [\Delta s_0(L) \cdot \vec{e}_1]^2 \rangle^{1/2}$, for 7 dBm input power vs. the pre-compensated length of fiber. The red dot-dashed line is the contribution of the two-pulse collisions alone, the purple dashes line is the contribution of the four pulse collisions alone, the blue solid line is the combination of the two, so it is the observed value of the standard deviation of the polarization jitter along $\vec{e}_1$. Along $\vec{e}_3$, the contribution of the two-pulse collisions to polarization jitter is zero, and only the contribution of the four pulse collisions is effective, and its variance is equal to the variance of the four pulse collisions along $\vec{e}_1$. Consequently, the purple dashed curve represents the observed standard deviation of the fluctuations of the third component of $\vec{s}_0$, that is $\langle [\Delta \vec{s}_0(L) \cdot \vec{e}_3]^2 \rangle^{1/2}$. The same expression may be obtained for the standard deviation of the term parallel to $\vec{e}_2$, hence being $\vec{s}_0$ parallel to $\vec{e}_2$, to the fluctuations of the pulse amplitude [the second term at left hand side of Eq. (7)]. Scattered symbols represent the results directly obtained from simulations, with the exception of the symbols over the two-pulse collision curve, which have been inferred using $\langle [\Delta \vec{s}_0(L) \cdot \vec{e}_1]^2 \rangle^{1/2}_{2-\text{pulse}} = \{ \langle [\Delta s_0(L) \cdot \vec{e}_1]^2 \rangle - \langle [\Delta s_0(L) \cdot \vec{e}_3]^2 \rangle \}^{1/2}$. The imperfect agreement at low pre-compensation is probably caused by the small depolarization of the pulses induced by the nonlinear interaction, more effective for small pulse pre-dispersion. The simulations were performed using the Manakov equation, yet the full equations including random mode coupling gave in our numerical example identical results if the fiber PMD did not exceed 0.05 ps/km$^{1/2}$, and results within 10% if the fiber PMD did not exceed 0.1 ps/km$^{1/2}$.

A possible way to significantly reduce the polarization scattering is polarization interleaving. If the two orthogonally polarized channels are offset by half of a symbol time, the interaction is between pulses either parallel or orthogonally polarized and two-pulse collision induced polarization rotation is to first order absent. This approach is expected to be effective only when two-pulse scattering is dominant over multiple-pulse scattering, that is for moderate amounts of pre-compensation, because four-pulse interactions produce polarization scattering also when all pulses are either co- or cross-polarized. To verify the effect of channel interleaving, we show in Fig. 2b by solid lines and in a logarithmic scale the standard deviation of the fluctuations of the

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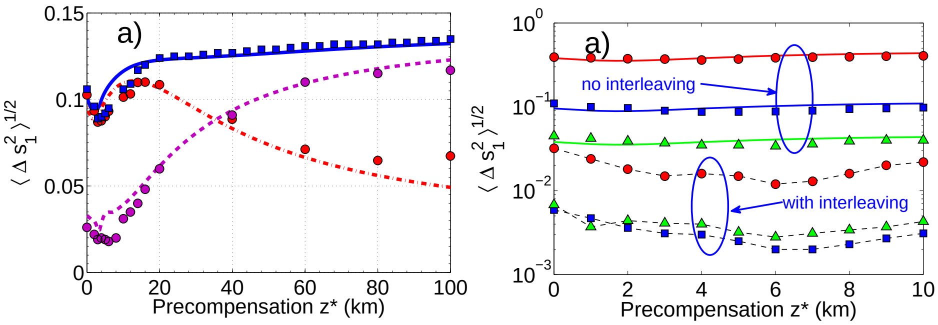

Fig. 2. a) Standard deviation of the first component of the Stokes vector, $\langle[\Delta\vec{s}_0(L)\cdot\vec{e}_1]^2\rangle^{1/2}$, for 7 dBm input power, vs. the pre-compensated length of fiber. Red dot-dashed curve: two-pulse collisions only; purple dashed curve, four pulse collisions only; blue solid curve, complete polarization jitter. The purple curve is also the standard deviation of the third component of the Stokes vector, $\langle[\Delta s_0(L)\cdot e_3]^2\rangle^{1/2}$, because the two-pulse contribution does not give fluctuations along $\vec{e}_3$. b) Standard deviation of the first component of the Stokes vector, $\langle[\Delta\vec{s}_0(L)\cdot\vec{e}_1]^2\rangle^{1/2}_{2-\text{pulse}}$, for 3 dBm (lower solid curve and triangles), 7 dBm (intermediate solid curve and squares), and 13 dBm (upper solid curve and circles) average input power, vs. the dispersion pre-compensation z^* in km of precompensated fiber, with no interleaving. Scattered symbols are the results of simulations, solid lines the prediction of the theory. In the three lower curves, dotted lines connect the results of simulations with channel interleaving under the same conditions of the solid lines.

first component of the Stokes vector, $\langle[\Delta\vec{s}_0(L)\cdot\vec{e}_1]^2\rangle_{2-\text{pulse}}$ vs. the dispersion pre-compensation z^* obtained using Eq. (10), with no interleaving. Points show the results of simulations. The three curves refer to an average input power of 3 (lower solid curve, triangles), 7 (intermediate solid curve, squares) and 13 (upper solid curve, circles) dBm. In the same figures, dashed black lines connect triangles, squares and circles representing the result of simulations with pulse interleaving. Again, triangles, squares and circles refer to 3, 7 and 13 dBm input power. The curves show a reduction of the polarization jitter by more than one order of magnitude, down to a level compatible with that expected from the sole contribution of four-pulse collisions. The reduction of depolarization obtained with pulse interleaving relies on the validity of the Manakov equation, which neglects PMD, hence the benefit of this technique may become less significant as PMD increases.

4. Conclusions

We have shown that intra-channel collisions may introduce significant polarization scattering in systems in which non orthogonal polarizations are transmitted. This phenomenon is the intra-channel analogous of the inter-channel polarization scattering in wavelength division multiplexed transmission. A first order perturbation theory including both two-pulse collision and four pulse collisions and quantitatively predicting the expected amount of depolarization has been presented. Finally, we have predicted and verified by computer simulations that channel interleaving reduces polarization jitter by more than one order of magnitude compared to the case of synchronous channels.

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