

Impact of Cross-talk on Polarization Mode Dispersion Compensators

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Abstract— We demonstrate both experimentally and by simulation nonlinearity-induced depolarization in wavelength-division multiplexing, in which the Stokes vector of each channel rotates around a space-invariant pivot by a time varying angle. The rotation depends on the total instantaneous optical power in the fibre, the angle between the pump and probe, and the channel spacing. These are identified by simulation as the key factors that determine the nonlinear-induced performance degradation on polarization mode dispersion compensators. They are validated by experiments.

Index Terms— optical fibre communications, polarization, nonlinearities, polarization mode dispersion (PMD) and wavelength-division multiplexing (WDM).

I. INTRODUCTION

In a wavelength-division-multiplexed (WDM) system, the nonlinear effect of cross-phase modulation (XPM) induces a rapid change of the state of polarization (SOP) on each channel [1], even when polarization-mode dispersion (PMD) is not present. Such a nonlinear polarization effect, which depends on the total instantaneous optical power in the fibre, produces a time-dependent polarization change on the time scale of a single bit. The ensuing depolarization of the WDM channels may pose a serious limitation on those links where polarization-mode dispersion compensators are needed to reduce the PMD-induced system impairments. Such compensators, in fact, are designed to compensate a single WDM channel independently of the others, in the linear regime of propagation. Most of them [2]-[4] typically use a polarization controller, a polarization-maintaining fiber (PMF) with a fixed delay, and a feedback or a feedforward control signal, e.g., the degree of polarization (DOP) [2] or a linear combination of spectral lines of the output signal [3], [4]. The optimum coupling condition between the line and the compensator is found by monitoring the feedback signal, which is assumed to change relatively slowly on the PMD millisecond time scale.

Unfortunately, optical fibre has nonlinear birefringence, thereby causing the SOP to wander depending on the local

total power. This nonlinear effect can occur on nanosecond time scales and has serious implications on WDM systems, since many channels will be added and dropped along the link. In WDM links, the presence of other channels will rapidly alter a signal's SOP and dramatically reduce the instantaneous effectiveness of a PMD compensator.

Moreover, with the aim of predicting such efficiency reduction, the study of depolarization due to the interaction of Kerr nonlinearity and PMD has been tackled in several experimental and theoretical works [5]-[7]. In Ref. [5], the focus is on the analysis by simulation of the depolarization induced by self-phase modulation (SPM) and its dependence on the transmitted pulse chirp. Möller *et al.* [6] have experimentally shown that if the SOPs of the WDM channels are launched in such a way that the overall input DOP is minimized, then effects of XPM are also minimized and the output DOP is maximized. In this work we measure and analyze the dependence of crosstalk on optical power, the launch state of pump SOP relative to probe SOP and wavelength spacing. We find that our experimental results agree well with the simulation results.

II. THEORY

Signal propagation in a fibre with rapidly varying birefringence along the length of the fibre can be described by the Manakov-PMD equation without the nonlinear PMD term [7]. Consider the two continuous wave (CW) channel case with completely polarized pump and probe fields having peak powers P_p and P_s that are launched into a fibre with a given relative polarization angle θ in Stokes space. Assume the fibre PMD is small enough so that there is no polarization coupling (power exchange) between the parallel and perpendicular components of the probe with respect to the pump polarization.

It is known that when both probe and pump are CW, the Stokes vectors for the probe $\vec{s}(z)$ and pump $\vec{p}(z)$ perform a rotation around a time- and z -independent pivot $\vec{m}(z) = \vec{s}(z) + \vec{p}(z)$ [1], [7]. At any point z , the rotation angle is [8]:

$$\phi(z, t) = \frac{8}{9} \gamma P_m \int_0^z e^{-\alpha z'} p \left(t - d_{sp} z' \right) dz', \quad (1)$$

where the magnitude of the pivot $P_m = \sqrt{P_s^2 + P_p^2 + 2P_sP_p \cos \theta}$ depends on the relative polarization angle and peak powers of the probe and the pump respectively. γ is the nonlinear coefficient, $p(t)$ is the input pump intensity, $d_{sp} = D(\lambda_1 - \lambda_2)$ is the walk-off parameter with D the chromatic dispersion coefficient. If the transmitted power is much larger on one channel, such a channel remains practically fixed, since its Stokes vector is almost coincident with \vec{m} . It is such a time-varying rotation around an average angle that causes the depolarization of the probe signal, whose DOP is therefore decreased. The average angle is given by:

$$\langle \phi(z, t) \rangle = \left(\frac{1}{2} \right) \frac{8}{9} \gamma P_m L_{\text{eff}}, \quad (2)$$

where L_{eff} is the effective length over which the power is approximately constant.

Calculation of DOP is based on the Carousel model [1], which postulates that at the fibre output $z = L$, the SOP of the probe depicts in time a circular trajectory around the pivot, with a rotation angle that swings in time around an average angle value by an amount

$$\Delta \phi(L, t) = \phi(L, t) - \langle \phi(L, t) \rangle. \quad (3)$$

The DOP then is given by [9]

$$\text{DOP} = \sqrt{1 - \sin^2 \theta_s [1 - \langle \cos \Delta \phi(L, t) \rangle^2 - \langle \sin \Delta \phi(L, t) \rangle^2]} \quad (4)$$

where θ_s is the angle between the probe and the pivot. We can draw the conclusion from equation (4) that the larger the swing angle the smaller the DOP.

III. EXPERIMENTAL AND SIMULATION RESULTS

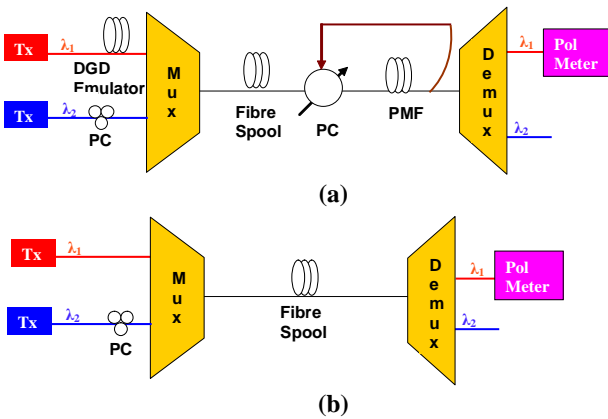
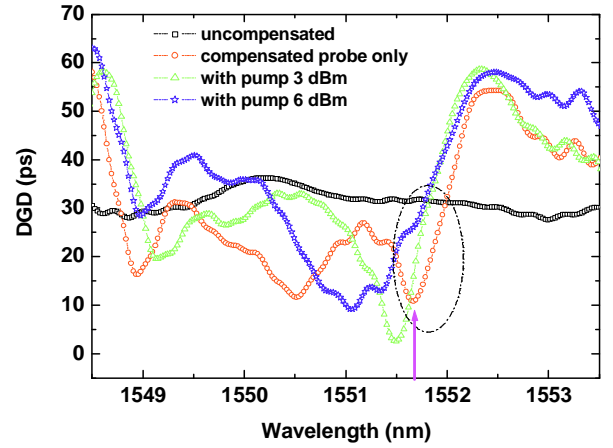


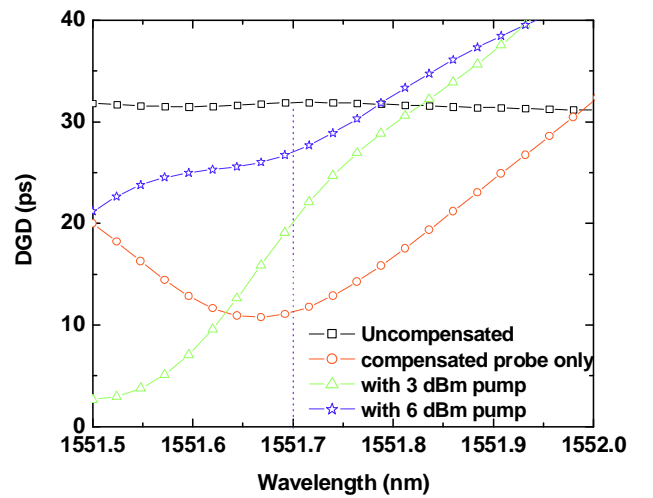
Figure 1: Experimental setup: (a) effect of nonlinearity on first-order compensator. (b) Investigation of orientation of pump SOPs on probe signal.

Based on the above theory, we investigate the performance of an ideal first-order PMD compensation system using the

probe-pump model. Figure 1(a) shows the experimental setup. λ_1 (operated at 1551.72 nm), is the probe channel, suffering the cross-talk induced polarization fluctuation. λ_2 (at 1550.92 nm), is the pump channel with high launched optical power; the channel spacing is set to 100 GHz. The probe channel goes through an emulator with Differential Group Delay (DGD) of 34 ps; it co-propagates with the pump channel in a low PMD transmission fibre, of 24 km and 2 ps DGD. At the receiver end, a fixed delay line (PMF) of 30 ps is used to compensate the first-order PMD. From figure 2, in the absence of the nonlinear effects i.e., without the pump channel, roughly 75% of the DGD is compensated, the remaining may be due to higher PMD and other dispersion effects. We notice that as the pump power increases, the DGD increases towards uncompensated value of DGD. This is elaborated in figure 2(b). In summary, the compensator's efficiency reduces and degradation rises as the pump power increases.

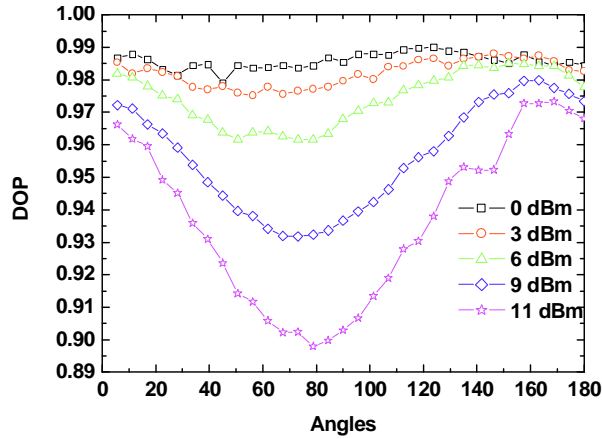


(a)

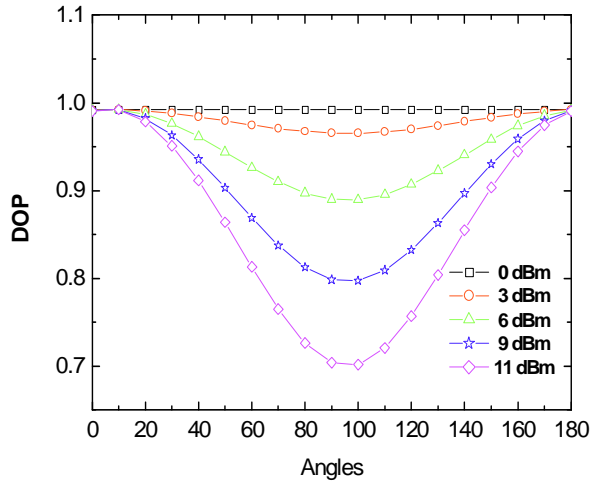


(b)

Figure 2: (a) measured Variation of DGD with wavelength at various pump signal powers. (b) Expanded section as indicated in (a) by a dotted circle.



(a)



(b)

Figure 3: (a) Experimental results of DOP dependence on relative launching angles at different pump signal powers; (b) Simulation results of DOP dependence on relative launching angles at different pump signal powers [9].

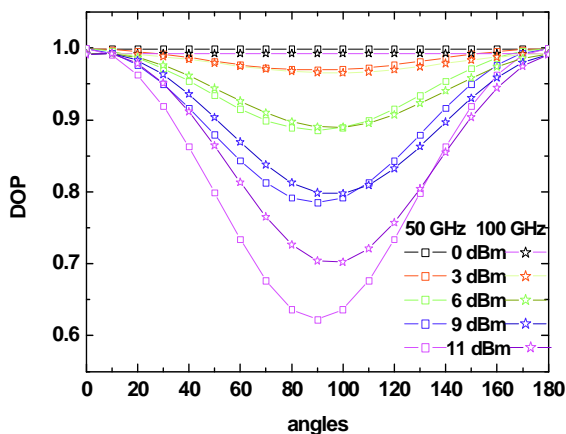


Figure 4: Simulation results showing a comparison of channel spacing at different launching powers and angles.

Here we show both experimentally and by simulation using VPI software [10] that cross-talk effects are responsible for nonlinear polarization evolution. This is done when we show DOP dependence on the relative pump-probe polarization angle. The pump signal is launched at various angles as we varied the pump powers (0 dBm – 11 dBm). Together with the probe signal, they co-propagate through a 24 km long SMF having a small PMD of 0.2 ps DGD so that the effect of PMD can safely be neglected. The channel spacing is 100 GHz.

All the plots in figures 3 (a) and (b) and figure 4 show the same V-shape. They agree well with the statistical results in [9], though there is a small difference between the simulation and the experimental results. This is due to the chromatic dispersion in the link. Such effect is not taken into account in the simulations. Generally, this shows that the dependence of the state of polarization on launching angles and channel spacing at given pump powers, leads to a depolarization of both channels. If the relative angle between the two channels is equal to 180° (cross-polarized channels) or 0° (co-polarized channels) in Stokes space, depolarization does not occur. The maximum depolarization appears around 90° . This shows that the cross-talk effects may lead to a distortion in the feedback signal of the compensator, since the power change in the probe signal will cause a PMD change in the probe. This renders the method of monitoring signal distortion using DOP inefficient in a PMD compensator.

IV. CONCLUSION

We have shown experimentally and by simulation that cross talk-induced depolarization can lead to a degradation of PMD compensator efficiency. These effects should be taken into account when assessing the impact of PMD in long haul transmission systems.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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