Reduction of Nonlinear Penalties Through Polarization Interleaving in $2 \times 10$ Gb/s Polarization-Multiplexed Transmission

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Abstract—We simulated the nonlinear transmission penalties induced through cross-phase modulation related depolarization in $2 \times 10$ Gb/s polarization-multiplexed (POLMUX) transmission. We find that launching adjacent wavelength-division-multiplexed channels with a 180° relative state of polarization shift results in a significant decrease in nonlinear transmission penalties and allows for longer distance POLMUX transmission.

Index Terms—Cross-phase modulation (XPM), nonlinearity tolerance, polarization interleaving, polarization multiplexing (POLMUX), wavelength-division multiplexing (WDM).

I. INTRODUCTION

In POLARIZATION multiplexing (POLMUX), two signals are transmitted at the same wavelength with orthogonal states of polarization (SOP). POLMUX has been a long standing promise in optical communications and has been successfully used in both record breaking laboratory experiments [1], [2] and field trials [3]. However, whereas POLMUX transmission is in theory very promising for an ideal optical fiber, the maximum reported transmission distance of dense wavelength-division-multiplexing (WDM) nonreturn-to-zero (NRZ) POLMUX transmission is to the best of our knowledge limited to 300 km [3]. This short transmission distance for POLMUX is generally attributed to a decrease in polarization-mode dispersion (PMD) tolerance in comparison to non-POLMUX transmission [4], [5]. However, for $2 \times 10$ Gb/s POLMUX NRZ transmission, the limiting effect is not the influence of PMD, but rather a result of cross-phase modulation (XPM) [5].

This depolarization penalty is due to interchannel cross-polarization modulation (XPolM) in POLMUX transmission, which depends on the total launch power of all copropagating channels and is independent of the channel spacing [6].

In this letter, we discuss multichannel nonlinear transmission penalties in $2 \times 10$ Gb/s POLMUX NRZ transmission. We introduce a new type of polarization interleaving [9], as a technique to avoid the interchannel penalties. Theoretical and simulation results show that transmission impairments can be decreased significantly. However, the proposed technique suffers from a increased PMD sensitivity.

II. XPolM

A. Simulation Setup

In order to study the effects of XPolM, we simulate between 1 and 11 channels on a 100-GHz grid, over 100 km of standard single-mode fiber with a split-step algorithm. Each polarization channel is modulated with a 10-Gb/s NRZ signal and a different 2-ad 1 pseudorandom bit sequence. For each WDM channel, two polarization channels with orthogonal polarization are multiplexed on the same wavelength and are time-synchronized on the bit level to prevent changes in the SOP within the bit period [5]. No polarization interleaving is used, so all WDM channels have the same SOP. A predispersion of $\pm 510$ ps/nm and zero accumulated dispersion are used. The influence of PMD is neglected, but birefringence and nonlinear interaction between the principal SOP are simulated. After transmission, the polarization channels are demultiplexed assuming an ideal polarization beam splitter. To study the influence of nonlinear impairments, the launch power is varied, and noise is not included.

B. Simulation Results

Fig. 1(a) and (b) illustrates the launch power dependence of 10-Gb/s non-POLMUX and $2 \times 10$ Gb/s POLMUX transmission, respectively. The eye-opening penalty (EOP) is defined as twice the mean signal intensity divided by the maximum eye opening available for 20% of the bit period. Note that the results show the worst-case EOP of both POLMUX channels. In POLMUX transmission, the interchannel nonlinear penalty increases strongly with the number of copropagating channels, which is evident from the EOP in Fig. 1(b). In contrast, the interchannel penalties in XPM dominated non-POLMUX transmission depend on the channel launch power of the nearest neighbors. Comparing one- and nine-channel WDM transmission, for a 1-dB EOP, it is evident that the transmission penalty is significantly smaller for non-POLMUX (3.4 dB) than for POLMUX (11.7 dB) transmission.

III. INTERLEAVED POLMUX

The XPolM penalty makes POLMUX transmission questionable for long-haul WDM transmission. However, by launching adjacent WDM channels with a 180° relative SOP shift (90° in
Jones vector notation), i.e., employing polarization interleaved transmission, interchannel nonlinearities can be reduced.

A. Theoretical Considerations

Interleaved POLMUX transmission deterministically spreads out the SOP of the WDM channels over the Poincaré sphere, by changing the SOP of the even WDM channels with respect to the uneven channels. Note that the SOP of a WDM channel is rotated after POLMUX of the two NRZ channels, so the orthogonality of POLMUX channels remains unchanged. Polarization interleaved POLMUX transmission bears a strong similarity to polarization interleaved transmission for non-POLMUX transmission, where adjacent channels are transmitted in orthogonal SOPs. In non-POLMUX transmission, this reduces the influence of interchannel transmission penalties such as XPM and FWM. However, in polarization interleaved POLMUX transmission, a signal is transmitted in both orthogonal SOPs of each copropagating WDM channel. So polarization interleaving cannot reduce XPM and FWM penalties in POLMUX transmission. However, we show here that polarization interleaved transmission (as depicted in Fig. 2) does reduce the XPolM penalty, due to a reduction in depolarization.

First we consider the slightly different case of two copropagating channels. Using the Manakov equation [10], one can show that the nonlinear polarization shift induced on a channel \( A \) through a second copropagating channel \( B \) at a different wavelength is equal to \( \frac{\partial S_A}{\partial z} = 8/9 \gamma P_0 (S_A \times S_B) \), where \( S_i \) denotes the Stokes vector of channel \( i \), \( \gamma \) the nonlinear coefficient, \( P_0 \) channel power, and \( z \) transmission distance. When \( S_B \) is parallel or antiparallel with respect to \( S_A \), the nonlinear polarization shift equals zero, and the influence of the copropagating channel is cancelled. However, for POLMUX signals, the instantaneous SOP depends on the transmitted bit sequence. Consequently, by launching channels \( A \) and \( B \) on parallel SOPs, the nonlinear polarization shift is not minimized for every possible bit sequence. Worse, it can be shown that choosing parallel SOPs for all channels maximizes the variance of the nonlinear polarization shift, which results in depolarization. However, when the Stokes vector of channels \( A \) and \( B \) are orthogonal, the magnitude of the vector product \( |S_A \times S_B| \) is equal to the magnitude of the vector \( S_A \). In that case, the nonlinear polarization shift is independent of the bit sequence in the copropagating channel, which effectively cancels the influence of XPolM. For two copropagating channels, this holds true for a 180° relative SOP shift with a 180° periodicity. Fig. 3(a) shows the magnitude of the vector product \( |S_A \times S_B| \) as a function of the relative orientation of the two Stokes vectors.

For multiple copropagating channels, it can be shown that a 180° relative SOP shift minimizes the nonlinear depolarization. With more than two copropagating channels, the vector product in the Manakov equation can be written as \( |S_A \times \sum_{i \neq A} S_i| \) or \( |S_A \times S_B + S_C| \) with \( S_0 \) the sum vector of SOPs of all copropagating channels. For three copropagating channels, the sum vector \( S_0 = S_B + S_C \) equals zero when the Stokes vector of channels \( B \) and \( C \) are antiparallel. The nonlinear polarization shift is then only dependent on channel \( A \), which cancels the influence of XPolM. For multiple copropagating channels (\( \geq 3 \)), the influence of polarization interleaving is, therefore, based on the observation that the sum of the average Stokes vectors of all copropagating WDM channels is zero. The XPolM influence is, however, not fully cancelled, because the instantaneous SOPs of POLMUX signals do not fully cancel out. Note that in the proposed polarization interleaving scheme, not every channel SOP is optimized independently, but adjacent channels have simply a 180° relative SOP shift. This only minimizes XPolM penalties for specific number of copropagating channels since the sum of the Stokes vectors is not always minimized.

Fig. 3(b) shows the magnitude of the vector product for five copropagating channels when the polarization of the even channel is rotated and the polarization of the uneven channels is kept constant. This clearly shows that a 180° polarization shift between adjacent channels maximizes the vector magnitude and minimizes interchannel XPolM penalties in POLMUX transmission for multiple copropagating channels.
Reduction of the XPoM penalty in interleaved POLMUX transmission is based on the SOP of all copropagating channels, contrary to only that of the most adjacent channel in interleaved non-POLMUX transmission. A side effect of the dependency on the combined SOPs is that XPoM is not minimized for any given number of copropagating channels, as visible through the difference in nonlinear tolerance in Fig. 5. The nonlinear tolerance for the center channel is only maximized with an even number of copropagating channels at both sides of the center channel (e.g., five and nine channels).

Interleaved POLMUX transmission is very promising to reduce interchannel nonlinear penalties. However, PMD negatively affects interleaved POLMUX transmission through a wavelength-dependent change of the SOP. This cancels the relative polarization difference between copropagating channels and reduces the effect of polarization interleaving. Hence, the influence of PMD will be more severe for polarization interleaved POLMUX transmission than for noninterleaved POLMUX transmission.

IV. CONCLUSION

Interchannel XPoM transmission penalties strongly limit the transmission tolerances of POLMUX NRZ transmission and restrict its use in long-haul nonlinear transmission systems. Through simulations, we have shown that the influence of XPoM transmission penalties on POLMUX NRZ transmission can be reduced significantly through polarization interleaved transmission of the WDM channels, whereas, it cannot be reduced through an increase in channel spacing. The maximum allowed launch power for a given nonlinear penalty increases by 7.8 dB when nine WDM POLMUX channels are interleaved. However, due to PMD, the benefit of polarization interleaving is decreased making the technique less suitable for long-haul transmission links.

REFERENCES