A Compensator for the Effects of High-Order Polarization Mode Dispersion in Optical Fibers

Mark Shtaif, Antonio Mecozzi, Moshe Tur, and Jonathan A. Nagel

Abstract—**We present a polarization mode dispersion compensator for the rotation of the principal states with frequency. This compensator requires only two control elements more than existing first-order compensators. These are the position of one polarization controller and the setting of a single delay. With the proposed scheme, compensation for first order can be decoupled from the compensation for higher orders and controlled independently. The effect of the compensator on signal transmission is evaluated with extensive numerical simulations.**

Index Terms—**Optical communication, polarization mode dispersion (PMD), PMD-compensation.**

IN RECENT YEARS, polarization mode dispersion (PMD) in optical fibers has become one of the major obstacles to the increase of transmission rates in wavelength-division multiplexing (WDM) systems. The first-order effect of this phenomenon can be quite simply described in terms of a group delay that is created between two components of the transmitted signal propagating along the fiber principle axis. In reality, this description seems to be insufficient for signal bandwidths that are relevant in optical communications, and distortions due to the effect of higher order PMD become visible [1]. PMD compensators that are designed for the new generation WDM systems will need to correct for such high-order effects. The main disadvantage of high-order PMD compensators suggested so far is that they require control over a large number of parameters [2]. In addition, the compensation for the various orders is coupled and needs to be done simultaneously. The compensator proposed here requires only one polarization controller and one adjustable delay in addition to what is needed for first-order compensation. In addition to first-order PMD, we compensate for the precession of the rotation axis defined by the transmission matrix of the fiber. Contrary to common wisdom, such compensation involves a combination of all PMD orders, where the orders are defined in terms of a Taylor expansion of the PMD vector in frequency as in [3]. In this paper, we will show that this description is consistent with the behavior of actual fibers in many cases.

While the most common definition of PMD orders is based on the Taylor expansion of the PMD vector in frequency [3], there is no reason to believe that this is the most natural description of actual fibers over a range of frequencies where first-order PMD is insufficient. The proposed compensator is based on the observation that within a limited bandwidth, the rotation axis defined by the transmission matrix of the fiber tends to perform precession at a nearly constant rate. It is important to note that this description is not second-order PMD in its common definition given in [3], nor does it correspond to a pure precession of the PMD vector, or of the principal states [4]. In fact, the PMD vector follows a more complicated path in Stokes space, which can only be approximated as precession in a small vicinity of the carrier frequency.

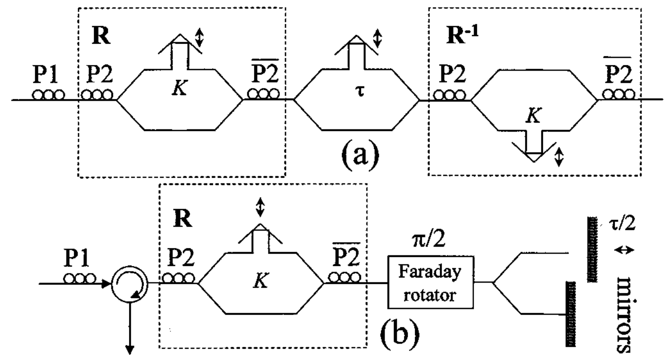

Fig. 1. (a) Schematic of PMD compensator. $P1$, $P2$, and $\overline{P2}$ are polarization controllers, and all splitters are polarization beam splitters. K and τ are variable delays. The last polarization controller is shown only for conceptual reasons and it is not required in practice. (b) An alternative implementation of the same compensator with only two delays. The Faraday mirror performs a rotation of $\pi/2$ in Stokes space. Note that by fine tuning of the delays K and τ so that they do not affect the polarization of the central frequency, the compensation for first- and higher orders can be completely decoupled from each other. The setting of $\overline{P2}$ has a fixed relation to the position of $P2$.

The Jones matrix describing this compensator is given by

$$\mathbf{M}(\omega) = \mathbf{R}^{-1}(\omega\vec{K}) \begin{bmatrix} \exp(i\omega\tau/2) & 0 \\ 0 & \exp(-i\omega\tau/2) \end{bmatrix} \times \mathbf{R}(\omega\vec{K})\mathbf{R}(\vec{\theta}) \qquad (1)$$

where ω denotes the deviation from the central angular optical frequency and $\mathbf{R}$ denotes a unitary Jones matrix whose effect is equivalent to rotation in Stokes space. The argument of this operator is a three-dimensional Stokes vector whose orientation is the axis of rotation and whose magnitude is the rotation angle. In (1), τ is the differential group delay and K is the precession rate of the rotation axis defined by $\mathbf{M}$. $\mathbf{R}(\vec{\theta})$ is used to transform the principal states at the fiber output into linear polarizations. The straightforward implementation of the compensator is depicted in Fig. 1(a). The first rotation in (1) is frequency independent and can be trivially implemented by a single polarization controller $P1$. The second and fourth rotations $\mathbf{R}(\omega\vec{K})$

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and $\mathbf{R}^{-1}(\omega\vec{K})$ are each implemented with two polarization controllers $P2$ and $\overline{P2}$, a polarizing beam splitter/combiner and a variable delay. The two polarization controllers $P2$ and $\overline{P2}$ perform exactly opposite transformations. The setting of $\overline{P2}$ can be obtained precisely from the position of $P2$ by using a predetermined lookup table. In practice, the $\overline{P2}$ polarization controller at the output of the compensator is obviously not required. The implementation in Fig. 1(a) is similar to the structure proposed in [5] for the PMD emulation. It involves two additional delay lines to first-order compensation and requires that the setting of the $P2$ and $\overline{P2}$ polarization controllers in the stage responsible for $\mathbf{R}(\omega\vec{K})$ isset exactly identical to the $P2$ and $\overline{P2}$ controllers that belong to $\mathbf{R}^{-1}(\omega\vec{K})$. Although such accuracy is possible in practice, a simpler implementation of the same compensator can be obtained with a Faraday rotator and a mirror, as depicted in Fig. 1(b). The Faraday rotator performs a $\pi/2$ rotation in Stokes space, and ensures that the transformation undertaken by the backward propagating field through the delay K is the inverse of the transformation undertaken during forward propagation. With the exception of an immaterial frequency-independent polarization rotation, the latter implementation is exactly equivalent to the previous one. Since the polarization controllers $P2$ and $\overline{P2}$ are fixed relative to each other, this compensator involves only two elements more than what is required for first—order compensation. These are the setting of $P2$ and the delay K. The feedback signal required for optimizing the compensation can be obtained in the same manner as in existing schemes of first-order compensation. It must be noted that an important requirement in all compensation schemes that involve more than a single variable delay is that the delays, once set, remain stable on the order of a single wavelength. This is so because a subwavelength variation of the delay of one stage rotates the polarization of the signal so that it is no longer compatible with the setting of the following stage. In the scheme proposed here, the delay of the first stage needs to be stabilized with this level of accuracy. Although such stability is a complication, it is feasible and can be implemented in several ways, which will be addressed separately. In most cases, an active feedback mechanism will be required.

A significant advantage in terms of controlling this compensator can be obtained (in both implementations) if the first and second rotations are adjusted such that they do not affect the polarization at the central optical frequency. In that case the setting of $\mathbf{R}(\omega\vec{K})$ and $\mathbf{R}^{-1}(\omega\vec{K})$ can be completely decoupled from the setting of the first-order compensation. Then, a natural algorithm for operating this compensator would be as follows: first set $K = 0$ and compensate for the first-order PMD, using only the first polarization controller $P1$ and the second delay τ. Then optimize the operation of the stages involving the rotations $\mathbf{R}(\omega\vec{K})$ and $\mathbf{R}^{-1}(\omega\vec{K})$. This scheme ensures that the performance of the higher order compensation is always better than that of first-order compensation, a situation that is not trivially achievable with other high-order compensation schemes. The adjustment of the first two rotations so that they do not alter the polarization at the central frequency can be obtained by fine tuning of the delays K and τ (within a single wavelength). Note that this does not add significant complication to the system because high stability of the first and second delays is required anyway.

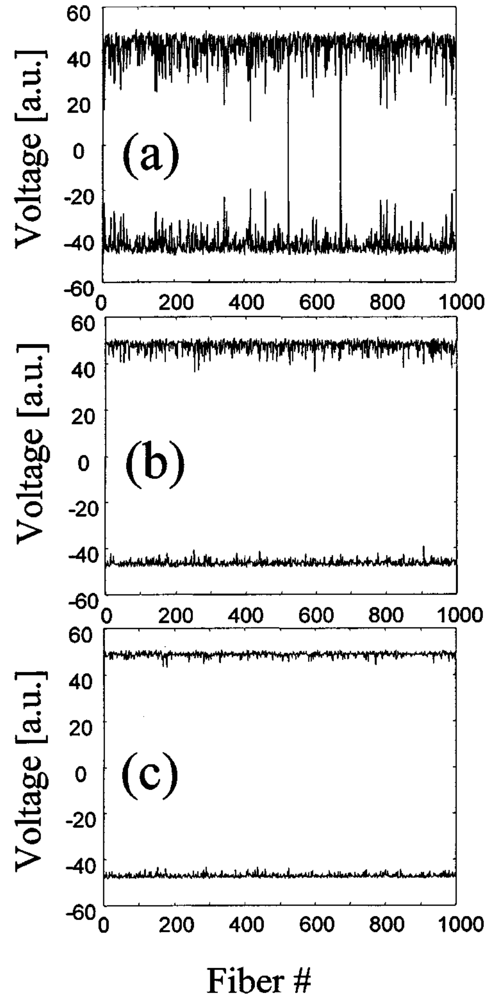

Fig. 2. Bottom and top of the eye obtained for the ensemble of the 1000 simulated fibers. Part (a) shows the uncompensated case, (b) the effect of a first-order compensator, and (c) the effect of the proposed compensator.

Our measure for the efficiency of the compensator is based on a comparison with a first-order PMD compensator that is applied to the same fiber. We have examined the operation of the proposed compensator on a pool of 1000 simulated optical fibers with an average PMD of 10 ps. To examine the effect of the compensator on signal transmission, we have performed a set of simulations with a 40-Gb/s pseudorandom nonreturn-to-zero signal. The launch polarization was chosen such that an equal amount of power was coupled into each one of the principal states at the signal central frequency. Our purpose in this paper is only to compare between the ultimate performances of the first-order compensator and the compensator that we propose. To achieve this, the compensation for first-order PMD was done by matching the PMD of the fiber at the central frequency, and the value of $\vec{K}$ was obtained from the rate of change in the direction of the PMD vector of the fiber in the vicinity of the central frequency. Although, in principle, an even better performance can be obtained in both cases by optimizing over all free parameters ($P1$, τ, K, and $P2$), we believe that our analysis provides a fair comparison of the two compensation techniques. Fig. 2 shows the bottom and the top of the eye obtained with each one of the 1000 fibers. The uncompensated case is shown

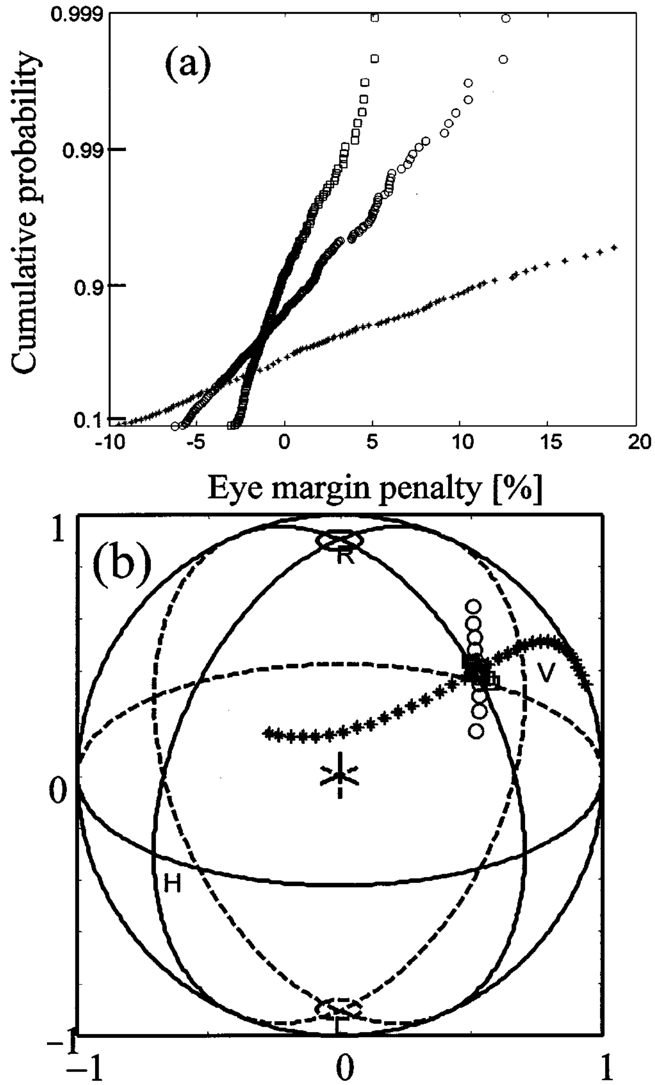

Fig. 3. (a) is the probability that the eye closure is smaller than a given value versus the eye margin penalty in percent for 40-Gbit transmission and 10-ps average PMD. The scale of the vertical axis is chosen such that a straight line corresponds to an integrated negative exponential distribution. Stars, circles, and squares correspond to the uncompensated case, first-order compensation, and proposed compensation, respectively. (b) is the output polarization at the output of the fiber (stars), the output polarization after first-order compensation (circles), and the polarization after the higher order compensator (squares). The average PMD is 10 ps, and the frequency band is 40 GHz. Note the improvement in degree of polarization achieved by the proposed compensator. Consistent results were obtained for all 1000 fibers.

in Fig. 2(a), the case of first-order compensation is described in Fig. 2(b), and the effect of the proposed compensator is shown in Fig. 2(c). The improvement achieved by the proposed compensator is self-evident.

To obtain more quantitative results, the distribution of the eye opening is plotted in Fig. 3(a). The horizontal axis corresponds to the eye closure in percents, and the vertical axis describes the probability that the eye closure is smaller than a given value. The vertical axis is scaled exponentially, namely, an exponential distribution would appear on this figure as a straight line. The crosses correspond to the uncompensated case, the circles to first-order compensation, and the squares to the proposed high-order compensator. The negative penalties result from the fact that PMD induced intensity fluctuations may, in some cases, open the eye, a phenomenon that is of no consequence to communication systems. The better performance obtained with the proposed compensator is evident. The origin of the good compensator performance lies in its capability of reducing depolarization caused by high-order PMD. This effect is shown in Fig. 3(b), which represents on the Poincarè sphere the depolarization that is observed in one particular fiber of the simulated sample when the frequency of a fixed polarization input signal is swept over a range of 40 GHz. The stars denote the effect of the fiber without any compensation, and the circles denote the effect of a first-order PMD compensator optimized to precisely remove the first-order PMD. The squares correspond to the effect of the proposed compensator. Note the large improvement in the degree of polarization obtained with the proposed compensator. This improvement in degree of polarization was observed consistently in all tested fibers.

To conclude, we have proposed a compensator to account for the precession of the rotation axis defined by the transmission matrix of the fiber. This compensator requires only two control parameters more than existing first-order compensators. With the proposed scheme, the compensation for first order is decoupled from the compensation for the higher orders and is controlled independently. Our results show a significant improvement in transmission performance over the case of first-order compensation only.

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