# Wideband all-order polarization mode dispersion compensation via pulse shaping

**M. Akbulut and A. M. Weiner**

*Purdue University School of Electrical and Computer Engineering, West Lafayette, Indiana 47907-1285*

**P. J. Miller**

*CRI Inc, 35-B Cabot Road, Woburn, Massachusetts 01801*

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We demonstrate the application of ultrafast pulse-shaping techniques for experimental wideband all-order polarization mode dispersion (PMD) compensation, for the first time to our knowledge. PMD is treated as arbitrary variations of state of polarization and phase versus wavelength, in an all-order sense. Consequently, two pulse shapers are implemented in a serial manner to compensate for the polarization and the phase spectra independently. We report compensation of subpicosecond pulses (14 nm bandwidth around 1550 nm) that are anomalously spread to more than 2 ps as a result of PMD. This PMD compensation scheme can potentially be a powerful and cost-effective solution for fiber optic telecommunication networks.

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Polarization mode dispersion (PMD) presents an intricate problem for ultrahigh-capacity telecommunications systems. PMD can be understood as arbitrary pulse distortions that are statistical in nature as a consequence of the random birefringences in single-mode optical fibers.[1] Generally, it is categorized in a Taylor series expansion framework in terms of the first-order PMD, second-order PMD, etc. The majority of the research so far is restricted to the first-order PMD limit. However, as the bandwidth of the telecommunications systems increase, PMD can no longer be investigated in the first-order approximation.[1–3] Considering that the first-order approximation applies only when distortion is limited to a couple of tenths of the nonreturn-to-zero bit period (or several tenths of the pulse width for return to zero), high-order PMD effects will become significant as bandwidths per WDM channel increase (e.g., future ultrafast time-divison multiplexing). Consequently, it will be logical to look at PMD with the more powerful approach of all-order PMD.[4–7] We choose to view PMD as arbitrary variations of the spectral phase and the spectral state of polarization (SOP), assuming no polarization-dependent losses (PDLs) or gains in the system. In this paper we demonstrate what we believe to be the first experimental application of ultrafast pulse shaping techniques to correct the full spectral variations (distortions) induced by PMD. Pulse shaping has been proved to be an effective way of implementing arbitrary phase and amplitude filter functions in the past,[8,9] and arbitrary polarization filter functions more recently.[4,5,10] For this work, a two-stage compensation scheme is implemented that is consistent with our view of PMD. A SOP pulse shaper and a phase-only pulse shaper are used in series to independently equalize polarization spectra and phase spectra in an attempt to compensate for essentially arbitrary PMD. We report PMD compensation for subpicosecond pulses (a 14 nm bandwidth around 1550 nm), originally distorted to more than 2 ps duration (several pulse widths), from which the original pulse was successfully recovered. Our two-stage all-order PMD compensation scheme has the potential to become a powerful and cost-effective solution for current or future ultrahigh-capacity, multichannel optical networks. In addition, running this system backwards can make it possible to explore simple all-order PMD emulation ideas.

Our experiment setup is shown schematically in Fig. 1. The source is a passively mode-locked fiber laser with a 50 MHz, 72 fs intensity FWHM pulse output. Part of this output is filtered to the 1542–1556 nm region (transform-limited pulse width of ~570 fs) and amplified with a commercial erbium-doped fiber amplifier (EDFA) to be used in the PMD compensation experiments, and the rest is used as a reference signal for the cross-correlation pulse measurements. PMD emulation is accomplished with two eight-piece segments of different-length polarization-maintaining (PM) fibers that are concatenated with random fast-axis angles. There is single-mode fiber after each eight-piece PM fiber segment that introduces additional polarization rotation between the segments. We either use a polarization controller before the PM fiber segments or change the sequence of the segments to obtain different PMD distortions from this apparatus. As the first stage of PMD com-

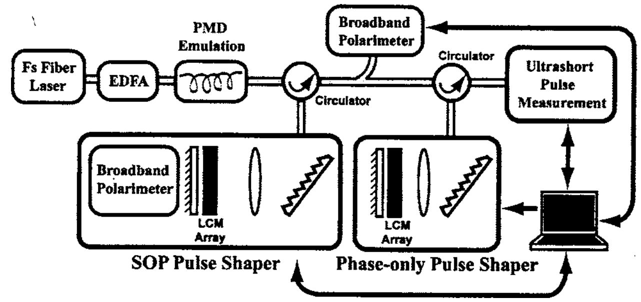


Fig. 1. Experimental setup.

pensation, the distorted signal is coupled to a double-pass reflective SOP pulse shaper. One requirement for this type of pulse shaper is that we needed a low-PDL grating, which in turn limited us in terms of the spatial resolution than can be achieved.[4,5] The liquid-crystal modulator (LCM) array in the SOP pulse shaper is a two-layer device with liquid-crystal orientations that is capable of rotating any arbitrary SOP input to a fixed linear state independently for each of its 128 pixels.[4,5] The feed-forward information that is required to program this LCM array is simply the knowledge of SOP versus wavelength. Recently, a fast wavelength-parallel polarimeter was developed in our laboratory, which is used in the PMD compensation work.[11] This polarimeter is a first in its class in terms of its wavelength-parallel operation (sensing more than 100 frequency components simultaneously) and speed (measuring in milliseconds with the potential for submillisecond operation). We integrated this polarimeter into our SOP pulse shaper with an innovative approach: we perform the polarization sensing inside the pulse shaper, using a partially transmissive mirror behind the LCM.

After the SOP pulse shaper, a small portion of the light going back into the fiber is tapped to check the quality of SOP spectrum correction. The remaining power goes into the second stage of our PMD compensator, namely, the phase-only pulse shaper. Given that only spectral phase variations remain after SOP equalization, the PMD problem transforms into a generalized chromatic dispersion compensation problem. Now it can be addressed by a phase-only pulse shaper that acts as a spectral phase equalizer for full pulse restoration.[12] We chose to implement a simpler pulse-shaper design here with a better spectral disperser that is not required to be low PDL, since the SOP versus wavelength at the input to this unit is actively stabilized by the prior SOP spectrum correction stage. The chromatic dispersion from the single-mode fibers in the setup was balanced with dispersion-compensating fiber and the residual dispersion from the alignment of our pulse shapers. All of the setup is fiber based except the two pulse shapers, which are fiber coupled. The insertion losses were 7.6 and 4.5 dB for the SOP and the phase-only pulse shapers, respectively, with a significant component of these losses due to the optical circulators.

We need to know the spectral phase and need to feed forward that information to the phase-only pulse shaper; however, PMD-induced phase spectrum is much more complicated than the simple quadratic or cubic functions. Given that *a priori* estimation of the PMD-induced random phase is very difficult, we chose to employ the well-known Gerchberg–Saxton algorithm to retrieve the phase information.[13] The temporal intensity information for this algorithm came from the cross-correlation measurements by use of the 72 fs reference pulse from the laser. Considering the distorted time-domain envelopes that are being measured, these cross correlations can be considered as good approximations of the time-domain intensity. It is important to note again that the programming of the pulse shapers is done in a feed-forward scheme without any complicated algorithms. However, for the phase-only pulse shaper we needed to iteratively apply the Gerchberg–Saxton algorithm to achieve a good estimate of the real spectral phase and thus achieve clean restored pulses.

To illustrate the technique, we now consider the experimental steps for a PMD compensation trial (Fig. 2). First, the time-domain pulse distortions produced by the PMD emulator are measured while both of the pulse shapers are set to inactive states (with all LCM pixels set for $2\pi$ phase). Second, the SOP versus wavelength distortions produced by the PMD emulator are measured and compensated. In the current experiments, the SOP spectrum is first measured with the SOP LCM set to a quiescent state (i.e., all pixels are set to $2\pi$ retardation). Then, the pixel settings required for polarization compensation are calculated and applied to the LCM, to produce a single polarization state independent of wavelength. The in-line broadband polarimeter is used to confirm this expectation. For real, dynamic PMD systems, the polarization data will have to be continuously read and compensated. In this case the measured SOP data could be inverted to yield the original SOP states prior to the LCM by using the known calibration of LCM polarization transformation versus pixel settings. The third step is to carry out the spectral phase retrieval. Finally, the phase-only pulse shaper is programmed to equalize the phase spectrum, and the restored clean pulse is measured by using the cross correlator.

Figure 3 illustrates a trial using two eight-piece PM fiber segments as the PMD emulator, with an average differential group delay estimated at 1.38 ps. With this emulator, a 792 fs input pulse is anomalously spread to more than 2 ps duration, with polarization versus wavelength varying dramatically over the Poincaré sphere. Considering that first-order PMD is valid only for broadenings of the order of several tenths of the pulse duration,[1–3] this is clearly a very high degree of PMD that can essentially be categorized as all-order PMD. After compensation, the pulse is restored to almost a single polarization, and the duration is reduced to 696 fs—better than the input pulse. In this case, it appears that residual chromatic dispersion in the system was also compensated by the phase-only pulse shaper. To observe a different PMD trial, we reversed the fiber segments of the PMD emulator (average differential group delay now estimated at 1.29 ps) and adjusted the input polarization to these segments. Also, we compressed our input pulse to a nearly transform limited ~576 fs duration. After compensation, the distorted signal was again restored to nearly a single polarization state, and the duration was reduced to 631 fs (with sidelobes below 15 dB) (Fig. 4). It is interesting to point out that the SOP pulse shaper unavoidably introduces additional spectral phase variations during the

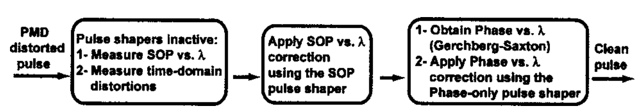


Fig. 2. Steps for a PMD compensation trial.

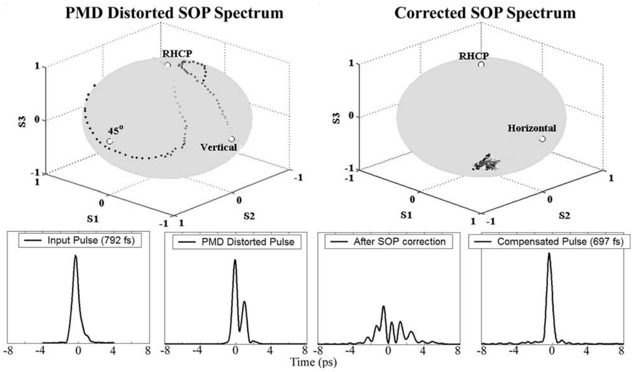


Fig. 3. PMD Compensation for 16-piece PM fiber distortion. Top left, polarization spectrum after PMD; top right, corrected SOP spectrum (1542–1556 nm range). Bottom, left to right, pulse measurements input, after PMD distortion, after SOP correction, fully PMD compensated.

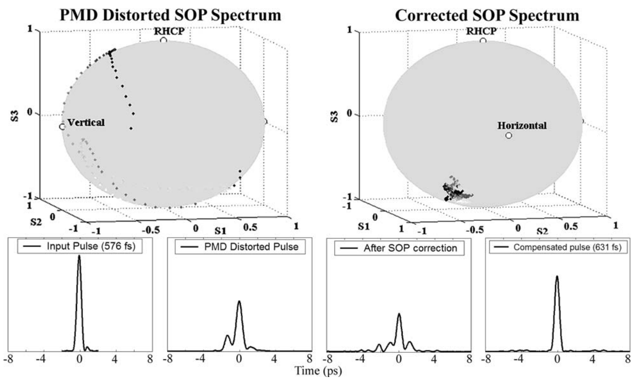


Fig. 4. PMD Data for another 16-piece PM fiber realization. Top, polarization spectra; bottom, pulse measurements, arranged as in Fig. 3.

process of SOP correction. This usually manifests itself as larger time-domain distortions compared with those just after the PMD emulator. Even so, the phase-only pulse shaper is capable of equalizing all of the spectral phase to give a clean restored pulse in each case. The small sidelobes that appear in the recompressed pulses may arise from insufficient spectral resolution or imperfect phase estimation.

While experiments to date were carried out with static PMD emulators, the programmability of the LCM arrays provides the capability to compensate for dynamic PMD. Although the refresh rates of our current LCM devices are in the tens of milliseconds range, it is possible to approach few millisecond rates with liquid-crystal technology. For dynamic all-order PMD compensation, a phase estimation technique with improved speed and robustness will be required. Once realized, it will be interesting to test the performance of the all-order compensator in a full lightwave systems context.

In conclusion, we have demonstrated the first experimental all-order PMD compensation scheme for wideband signals using ultrafast pulse shaping techniques. We were able to compensate for the PMD-induced distortions of the polarization spectra and phase spectra for subpicosecond pulses, restoring the dispersed pulses effectively each time. This two-stage, all-order approach can potentially be a powerful and cost-effective way of coping with PMD impairments in wideband optical fiber telecommunications systems. Our method should also be applicable to compensation for PMD in WDM systems. Additionally, our scheme can potentially enable emulation of all-order PMD with simple algorithms.

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