All-Order Polarization Mode Dispersion (PMD) Compensation in 10Gbit/s×4 OTDM System via Hyperfine Resolution Optical Pulse Shaper

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Abstract: We experimentally demonstrate optical compensation of all-order polarization mode dispersion with >50ps mean differential group delay in a 10Gbit/s×4 OTDM system using an optical pulse shaper with 1.6GHz/pixel resolution.

OCIS codes: (060.2330) Fiber Optics Communications; (260.5430) Polarization; (060.2340) Fiber optics components, (060.2370) Fiber optics sensors

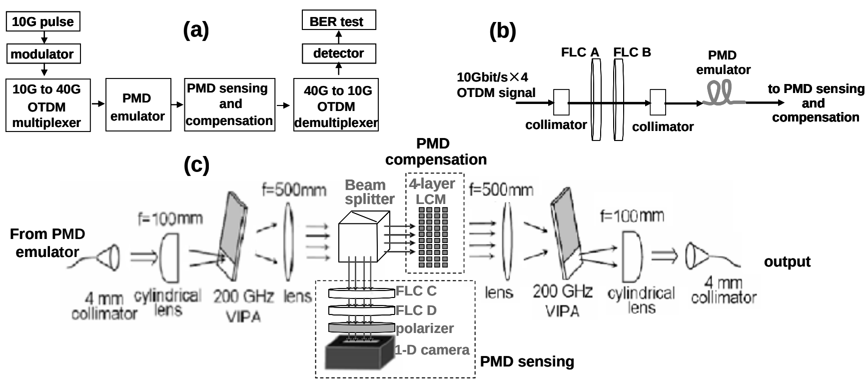
1. Introduction

Polarization mode dispersion (PMD) [1] is considered a major obstacle for ultrahigh-capacity fiber communication systems at 40 Gbaud/s and above. Although some electrical PMD compensation (PMDC) is possible, it is complex and expensive for high symbol rates, and to date experiments reaching to 40 Gbaud/s are limited. Furthermore, most research on PMDC, either electrical or optical, has been limited to the first- or second-order PMD regime, valid only for distortions small compared to the bit period or pulse width. Our group has previously demonstrated optical compensation of all-order PMD by using a hyperfine resolution optical pulse shaper [2]. In this previous work the compensator was tested with low repetition rate, isolated pulses, which were distorted and spread over >100 ps as a result of all-order PMD, then successfully restored via PMDC to their original 15 ps duration. Here for the first time we demonstrate such *all-order PMDC* in a lightwave system experiment at 40Gbaud/s (realized via 10Gbit/s ×4 optical time division multiplexing (OTDM) for compatibility with the speed of our bit error rate tester). We report successful compensation for PMD with mean differential group delay of 53.4 ps, more than twice the symbol period and well into the all-order regime. Our results show the possibility of compensating PMD distortion effects so large that they are usually viewed as intractable.

2. Experimental setup and method

As shown in fig. 1 (a), our experimental setup includes a transmitter, a PMD emulator, and a receiver. The transmitter comprises a 10GHz short pulse source, a modulator, and an optical 10G-to-40G OTDM multiplexer. The receiver includes PMD sensing optics and the PMD compensator, a 40G-to-10G OTDM demultiplexer, a 10GHz photodiode, and a bit error rate (BER) test set.

The pulse source starts with a CW laser, which is strongly modulated at 10 GHz to form a comb, then phase compensated via a pulse shaper to generate ~3ps FWHM pulses. Amplification and adiabatic soliton compression in a dispersion decreasing fiber generates a broad flat spectrum range from which we slice a smooth spectrum of ~120 GHz bandwidth FWHM (Fig. 2 (a)). For modulation we use both 10Gbit/s on-off keying intensity modulation and pseudorandom 0-π phase modulation for carrier suppression. The smooth spectrum resulting from carrier suppression, shown in Fig. 2(b), is more favorable for spectral polarimetry which we use in our PMD sensing scheme. The autocorrelation of the 10Gbit/s signal without PMD is shown in Fig. 2(c), from which we estimate a pulse duration of 5.9 ps FWHM. The 10G-to-40G OTDM multiplexer generates four decorrelated channels from the original 10 Gb/s pulses. All channels have the same state of polarization (SOP) before going to the PMD emulator. The homemade PMD emulator is the concatenation of several polarization maintaining fiber sections with randomly set fast axes and different lengths. From our measurement [3] shown in Fig. 2(d), the differential group delay (DGD) vs. wavelength varies in 0-110 ps range with mean value of 53.4ps (9 times the width of the signal pulse and more than twice the symbol period). This puts us well into the regime where Taylor series approximations to the PMD break down and all-order PMD must be considered. As shown in Fig. 1(b), two ferroelectric liquid crystal cells are used to impose a sequence of four different polarization transformations onto the signal prior to the emulator, which is used to sense the frequency-dependent Jones matrix of the PMD [2,3]. The PMD sensing and compensation module is shown in Fig. 1(c). The spectrum of the input signal is dispersed in free space by a virtually imaged phase array (VIPA) [4] with 200GHz free spectral range. A polarization insensitive beam splitter directs a portion of the signal to our fast wavelength-parallel polarimeter [3], with the remaining signal going to a 128-pixel × four-layer liquid crystal modular (LCM) array for PMD compensation [2]. The spectral dispersion across the pixels of the LCM array and of the 1-dimensional camera (used in PMD sensing) are carefully matched, with a value of 1.6GHz/pixel. By sequentially transforming the launch polarization into the PMD emulator and measuring the frequency-dependent polarization of the output light for each launch, we are able to calculate the frequency-dependent Jones matrix of the emulator at each frequency sample. In the compensation process the first 3 layers of the LCM array are programmed to generate the inverse frequency-dependent Jones matrix. The 3rd and 4th layers also compensate isotropic spectral phase (generalized chromatic dispersion) introduced by the PMD compensation step. This combination realizes complete all-order PMDC. The home-made optical 40G-to-10G OTDM demultiplexer, realized by cascading two 10 GHz intensity modulator, gives a timing gate of 16.5ps FWHM.



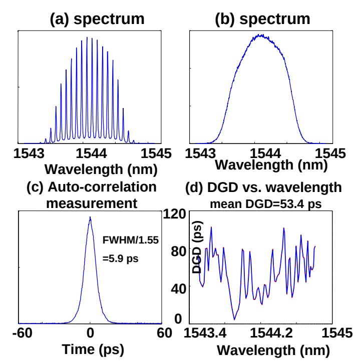


Fig. 1 (left). Experimental setup: (a) the whole setup; (b) PMD emulator; (c) PMD sensing and compensation
Fig. 2 (right) (a)spectrum of 10G short pulse; (b) spectrum of one 10Gbit/s channel with intensity modulation and carrier-suppression; (c) auto-correlation measurement of 10Gbit/s signal after it goes through PMD compensation module back-to-back; (d) PMD value of the PMD emulator.

3. Experimental results

We performed PMD compensation (PMDC) with the same PMD emulator in three cases: 10Gbit/s, 10Gbit/s×2 OTDM and 10Gbit/s×4 OTDM. We use a 50GHz photodiode before the 40G-to-10G demultiplexer to show the signal pulse before and after PMDC. After the demultiplexer, a 10G photodiode is used for BER test. The eye diagrams are shown in Fig. 3, using a 50 GHz photodiode before the demux (first two colums) as well as using a 10 GHz photodiode after the demux (last three columns), and the BER test results are shown in Fig. 4. In the 10Gbit/s case, Fig. 3 (a), PMD severely distorts the original 5.9 ps pulses, broadening them to approximately the 100ps range. Even at 10 Gb/s the PMD is large enough to introduce significant intersymbol interference. After compensation a clean eye is recovered, as shown in Fig. 3(b). The BER test shown in Fig. 4(a) shows that compensation improved the BER performance by several dB, making it close to the case without PMD down to a BER floor of ~10^{-8}. In the 10Gbit/s×2 OTDM case, as shown in Fig. 3 (f), the ISI is very strong. After compensation, Fig. 3(g), the signal is recovered and the crosstalk is significantly reduced. The BER test results in Fig. 4(b) show that before compensation, the best BER is in the range 10^{-1} to 10^{-2}. After compensation, the BER is again close to the no-PMD case down to a BER floor of ~10^{-8}. In the 10Gbit/s×4 OTDM case, as shown in Figs. 3(k,n), the ISI is so strong that the eyes completely close. After compensation, the eyes open, though some residual degradation remains. The BER test results in Fig. 4(c) show that before compensation, the bit error rate is essentially 50%. After compensation, the BER is similar to the no-PMD case (but with ~2dB power penalty) down to a BER floor of 10^{-6}, well into the range in which FEC is possible.

We notice the BER curves labeled 'back-to-back' in Fig. 4 degrade with increasing bit rate. Actually these curves correspond to operation without the PMD emulator but with passage through the PMDC setup (programmed to be quiescent). We have observed that passage through the PMDC imposes a small modulation onto the spectrum, which increases the tails on our pulses from roughly -30 dB intensity to -25 dB. We believe that this effect arises from misalignment of the free-space PMDC optics in the current experiment and is not fundamental. The observed

BER degradation (which does not occur if we bypass the PMDC optics as well) is attributed to this slight reshaping of our pulses, which no longer fully conform to the strict interferometric crosstalk requirements in OTDM systems.

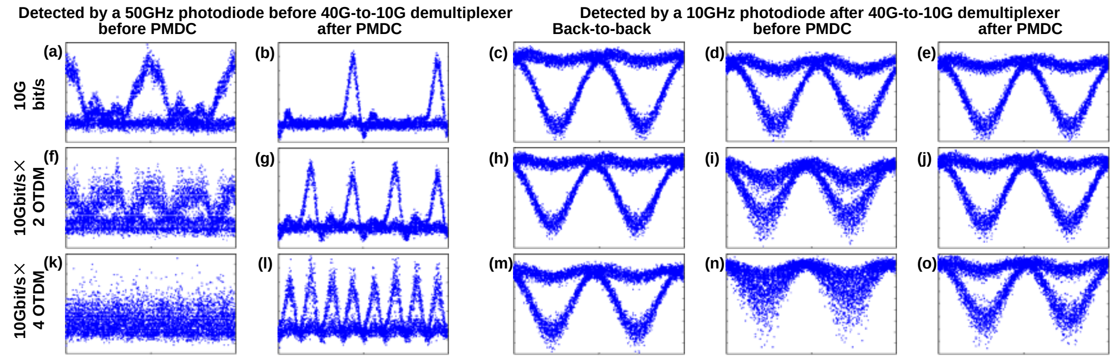


Fig. 3. Eye diagrams (200 ps time range): (a)-(e) 10Gbit/s; (f)-(j) 10Gbit/s×2 OTDM; (k)-(o) 10Gbit/s×4 OTDM.

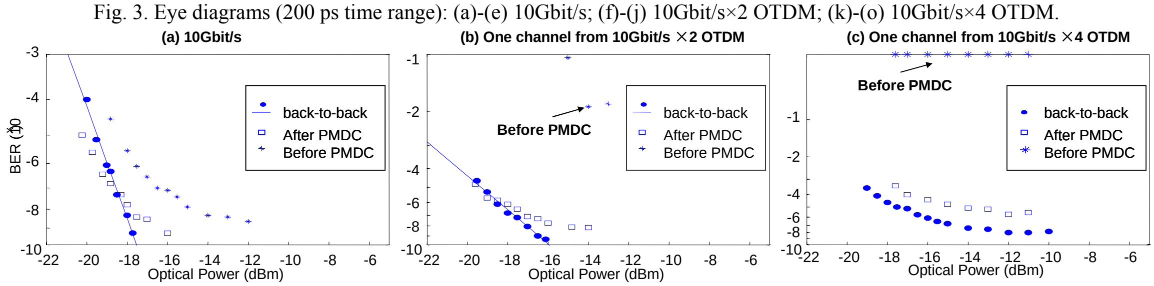


Fig. 4 BER test results. ‘Back-to’back’ means no PMD emulator, with compensator programmed to be quiescent.

In Figs. 3 and 4, the polarization switching used for PMD sensing is switched off during the compensation experiments. For Figure 5 we continuously switch between two polarization states at 2 kHz frequency during the compensation experiment. In both 10Gbit/s and 10Gbit/s×4 OTDM cases shown in Figs. 5(a)-(d), the polarization switching does not affect the recovered pulse. This provides evidence that the in-line polarization switching we use at the input, in order to allow real-time Jones matrix sensing, is compatible with simultaneous data transmission.

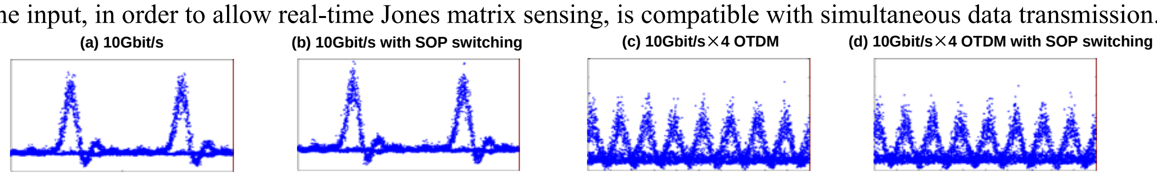


Fig. 5. Eye diagrams (200 ps time range). All are received by a 50GHz photodiode after PMDC. (a) and (b) 10Gbit/s; (c) and (d) 10Gbit/s×4 OTDM; (b) and (d) with input SOP to PMD emulator switching at 2kHz between 0 and 90 degree linear SOP.

4. Conclusion

We experimentally demonstrate feed-forward all-order optical PMD compensation in a 10Gbit/s×4 OTDM system with very large PMD (mean DGD >50ps) using a hyperfine resolution pulse shaper provisioned with a four-layer liquid crystal modulator array and frequency-dependent Jones matrix sensing. This shows the possibility of PMDC at 40G/s symbol rate for distortions so large their compensation is usually viewed as intractable. Furthermore, our all-optical approach can readily be extended to higher symbol rates (pulses down to the sub-ps range).

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