All-order polarisation mode dispersion compensation in 10 Gbit/s × 2 Pol-Mux system via hyperfine resolution optical pulse shaping

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By using wavelength-parallel polarimetry and hyperfine optical pulse shaping for sensing and compensation of the frequency-dependent Jones matrix, optical compensation of all-order polarisation mode dispersion is experimentally demonstrated with >40 ps mean differential group delay in a 10 Gbit/s × 2 Pol-Mux system (10% RZ).

Introduction: Polarisation division multiplexing (Pol-Mux) is an important method to improve spectral efficiency in lightwave communications. For Pol-Mux used in ultra-high-capacity fibre systems, polarisation mode dispersion (PMD) [1] not only distorts and broadens the signal, but also couples polarisation-multiplexed channels. In the case of large PMD, this coupling becomes strongly frequency-dependent. Moreover, PMD lowers Pol-Mux transmission tolerance to fibre nonlinearity and chromatic dispersion. Therefore, for fibre spans in which the PMD is not very small, PMD compensation (PMDC) is required [2]. Most research on PMDC, either electrical [3] or optical [4], has been limited to the first- or second-order PMD regimes, which are valid only for distortions that are small compared to the bit period or pulse width. Our group has used a hyperfine resolution optical pulse shaper for compensation of all-order PMD, for which the PMD varies strongly within the bandwidth of the optical signal [5]. 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. In other experiments using a similar scheme, but designed for larger optical bandwidth and ultra-short pulses, 800 fs pulses were fully compensated for after being distorted to >10 ps by all-order PMD [6]. Here we perform 10 Gbit/s × 2 Pol-Mux RZ (pulse width is ~9.4 ps FWHM) system experiments in which this scheme is demonstrated for compensation of all-order PMD with >40 ps mean differential group delay (DGD).

Experimental setup and method: Our experimental setup (shown in Fig. 1) begins with ~9.4 ps pulses (120 GHz bandwidth) spectrally sliced from a 10 GHz repetition rate modelocked laser. Pulses are modulated at 10 Gbit/s using on–off keying. In addition, pseudorandom 0–π phase modulation is used for carrier suppression, which gives a spectrum more favourable for our PMD sensing scheme. The signal is split, and then recombined with an eight-symbol delay for polarisation multiplexing. A PMD emulator is constructed by concatenating over 10 polarisation maintaining fibre sections with randomly set fast axes and different lengths. From our measurements [7] shown in Fig. 2*a*, the differential group delay (DGD) against wavelength varies rapidly within the optical spectrum, covering a range from nearly zero to 110 ps with mean value of 41.5 ps. The PMD sensing and compensation module is shown in Fig. 1*b*. The spectrum of the input signal is dispersed in free space by a virtually imaged phase array (VIPA) [8] with 200 GHz free spectral range. A polarisation insensitive beam splitter directs a portion of the signal to our fast wavelength-parallel polarimeter [7], with the remaining signal going to a 128-pixel × four-layer liquid crystal modular (LCM) array for PMD compensation [5]. The spectral dispersion across the pixels of the LCM array and of the one-dimensional camera (used in PMD sensing) are carefully matched, with a value of 1.6 GHz/pixel. By using a pair of ferroelectric liquid crystal cells (FLC) [7] to sequentially transform the launch polarisation into the PMD emulator (shown in Fig. 1*c*) and measuring the frequency-dependent polarisation of the output light for each launch, we are able to calculate the frequency-dependent Jones matrix of the emulator at each frequency sample [5, 7] (only one input polarisation channel is used in the sensing step). In the compensation process the first three layers of the LCM array are programmed to generate the inverse frequency-dependent Jones matrix. The third and fourth layers also compensate for the isotropic spectral phase (generalised chromatic dispersion) introduced by the PMD compensation step. This combination realises complete all-order PMDC. After PMDC the signal is polarisation demultiplexed back to 10 Gbit/s using a polarisation controller and an inline polariser, then characterised using a 50 GHz photodiode and sampling scope, and 10 GHz photoreceiver and bit error rate test set.

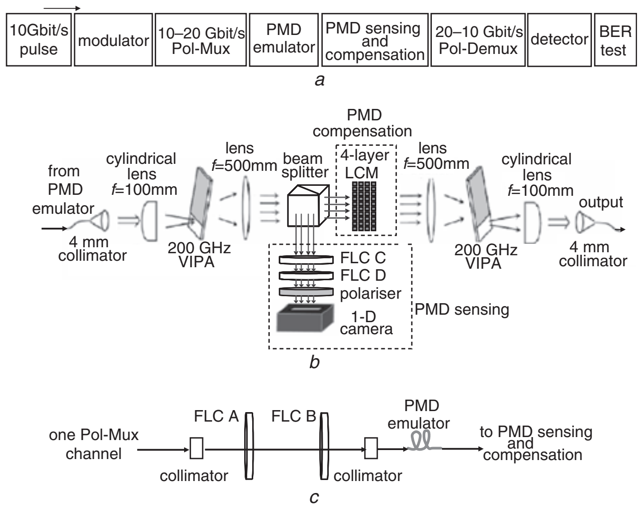

Fig. 1 *Experimental setup*

a Whole setup
b Details of PMD sensing and compensation
c Ferroelectric liquid crystal cells (FLC) and PMD emulator

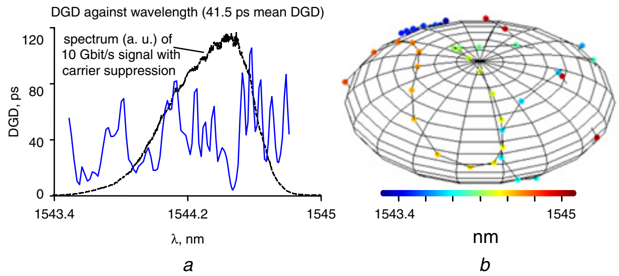

Fig. 2 *PMD value of PMD emulator and output polarisation against wavelength of one Pol-Mux channel*

a PMD value (DGD against wavelength) of PMD emulator
Spectrum of 10 Gbit/s signal with carrier suppression is overlaid
b Output polarisation against wavelength of one Pol-Mux channel after PMD emulator

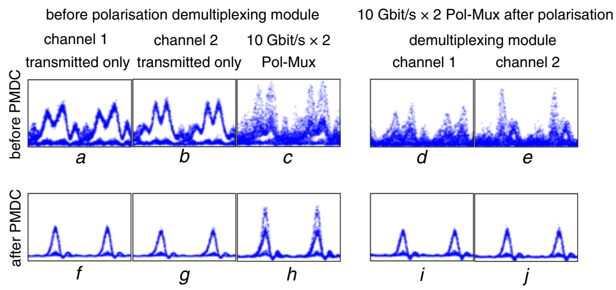

Fig. 3 *Eye diagrams (200 ps time range) arranged in two rows and five columns*

Rows: first row (*a–e*) is before PMDC; second row (*f, g*) is after PMDC
Columns: first three columns are grabbed before Pol-Demux module for channel 1 (*a, f*), channel 2 (*b, g*) and two channels muxed together (*c, h*); last two columns are grabbed after Pol-Demux for channel 1 (*d, i*) and channel 2 (*e, j*)

Experimental results: The eye diagrams detected by a 50 GHz photodiode are shown in Fig. 3. Figs. 3*a–e* are before PMDC. PMD severely distorts the original ~9.4 ps pulses, broadening them to over 100 ps (Figs. 3*a* and *b*). Moreover, for each channel, the polarisation against frequency traces show complicated trajectories on the Poincaré sphere (one channel is shown in Fig. 2*b*). Thus two Pol-Mux channels couple together and interfere severely as shown in Fig. 3*c*. After demultiplexing one channel from two, the eyes are closed, as shown in Figs. 3*d* and *e*. After PMDC the distorted signal is recovered, and the interference between channels is strongly reduced. Thus, prior to demultiplexing the eye for 10 Gbit/s × 2 Pol-Mux exhibits three clear levels (at 0, 1 and 2), as is expected when these channels are uncoupled (Fig. 3*h*). Moreover, after demultiplexing, the eye for each channel is restored to excellent quality. BER test results for both channels after demultiplexing are shown in Fig. 4. We use the BER of the no-PMD case as a back-to-back reference, which means the PMD emulator is taken out. With the emulator the bit error rate without PMD compensation is essentially 50%. After compensation, the BER is close to the no-PMD case, with almost no power penalty for channel 1, and about 1.5 dB power penalty for channel 2.

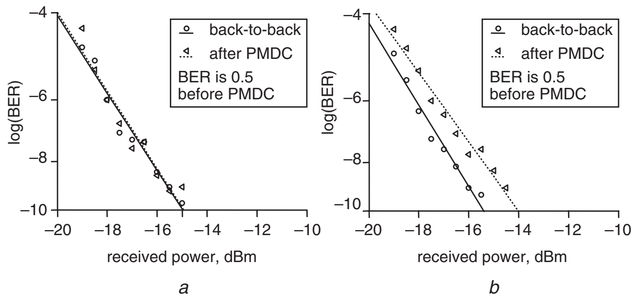

Fig. 4 *BER test results for each channel after demux from 10 Gbit/s × 2 Pol-Mux*

BER is 0.5 without PMDC and is not plotted
a Channel 1 (circle: back-to-back; triangle: with PMDC)
b Channel 2 (circle: back-to-back; triangle: with PMDC)

Future improvement: The degree of polarisation (DOP) is 0 if two Pol-Mux channels have the same optical power. Thus for SOP sensing in this experiment, we allow only one channel to launch, and temporarily block the other. However, if we set the two channels for different power, say one has power 1 and the other has power r ($0 < r < 1$), we can measure SOP with DOP equal to $(1 - r)/(1 + r)$ when both channels are launched. This scheme may allow continuous PMD sensing for PMDC control during Pol-Mux transmission. Note that DOP decreases as r increases towards one, which reduces OSNR for SOP sensing, while small r will lead to low OSNR transmission for one of the channels. Therefore, an appropriate value of r will involve a trade-off between these factors.

Conclusions: We have experimentally demonstrated feedforward all-order optical PMD compensation in a 10 Gbit/s × 2 Pol-Mux 10% RZ system with large PMD (mean DGD >40 ps) using a hyperfine resolution pulse shaper provisioned with a four-layer liquid crystal modulator array and frequency-dependent Jones matrix sensing. The ~10 ps short pulse source we used here, along with previous isolated pulse experiments using a subpicosecond source [6], suggest that this approach may be extended to 40 Gbit/s × 2 Pol-Mux or higher symbol rates.

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