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Polarization mode dispersion compensation at 20 Gb/s with a compact distributed equalizer in $LiNbO_3$

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Abstract: *PMD of existing fibers impairs transmission at ≥10 Gb/s. We present a 43 ps PMD compensator in X-cut, Y-propagation* $LiNbO_3$ *with cascaded TE-TM converters and demonstrate successful operation at 20 Gb/s.*

Introduction: After fiber attenuation and chromatic dispersion, polarization mode dispersion (PMD) is the next biggest obstacle in the development of highest-capacity, long-haul optical communication systems. Unlike the foregoing, PMD is intricate to tackle because it may vary as a function of time. Previous work on optical PMD compensation has focused on selecting a principal state of polarization (PSP) of the transmission line [1] or implementing a compensator consisting of a small number of differential group delay (DGD) sections, separated by polarization transformers [2–4]. We have recently presented a distributed fiber-based PMD equalizer [5]. – Here PMD is compensated by functionally similar devices in X-cut, Y-propagation $LiNbO_3$. In contrast to optical PMD equalizers reported so far the integrated optics solution is compact, entirely non-mechanical, reliable, and features high speed.

Equalizer structure and device function: PMD can be modeled by DGD sections separated by polarization transformers. Graphically this corresponds to a sequence or profile of vectors in the 3-dimensional space of normalized Stokes vectors. A 1-section PMD compensator will just remove 1st-order PMD by introducing a DGD oriented so that the PMD vector sum is nulled. However, residual higher-order effects will typically result in >2 dB (or infinite) penalty if the canceled 1st-order DGD equals the bit duration T (or 1.4 T).

PMD equalizers with one or few sections need to have variable DGD sections in order to avoid trapping in side maxima during the control process. But a practical equalizer with more than one section can not tolerate variable DGD sections: Consider a DGD change of 52 ps of one section while the rest of the DGD profile should remain unchanged. This corresponds to 10,000 λ and means that one or more polarization transformers following the variable DGD section have to turn 10,000 times, which is incompatible with speed requirements.

The only viable possibility for near-perfect PMD compensation lies therefore in equalizers with fixed DGD sections. The section number should be so large that side maxima essentially coincide with the main maximum. An excess of total DGD of the compensator over that of the transmission line is not of concern because some adjacent compensator sections can be made to cancel each other. It can be shown that the polarization transformers need to be able to *endlessly transform any input polarization into a PSP of the following DGD section*.

The implementation of such TE-TM mode converters with coupling adjustable in both quadratures has been proposed many years ago [6]. Since X-cut, Y-propagation $LiNbO_3$ is required the natural birefringence (~0.26 ps/mm) can be used for DGD cancelation at the same time, thereby making the PMD equalizer truly distributed. In Fig. 1 the interdigital electrodes have periods equal to the optical beat length Λ, and subsequent interleaved combs are spaced by additional $\Lambda/4$ or $3\Lambda/4$ lengths. Operation is based on the electrooptic coefficient r_{51}. Depending on its phase each comb finger allows a small amount of mode coupling κ_1 with ±45° linear or κ_2 with right/left circular eigenmodes, respectively, of a waveguide section of length Λ. If $m >> 1$ comb fingers of like phases are connected to electrode E_{1i}, and m quadrature comb fingers to electrode E_{2i}, then the Jones matrix of the corresponding waveguide section is approximately [6]

$$\begin{bmatrix} \cos\varphi/2 & je^{-j\,\mathrm{arc}(\kappa_1+j\kappa_2)}\sin\varphi/2 \\ je^{j\,\mathrm{arc}(\kappa_1+j\kappa_2)}\sin\varphi/2 & \cos\varphi/2 \end{bmatrix} \text{ with retardation } \varphi = 2m\sqrt{\kappa_1^2+\kappa_2^2}\,.$$

The coupling phase in the off-diagonal elements is endlessly adjustable as required.

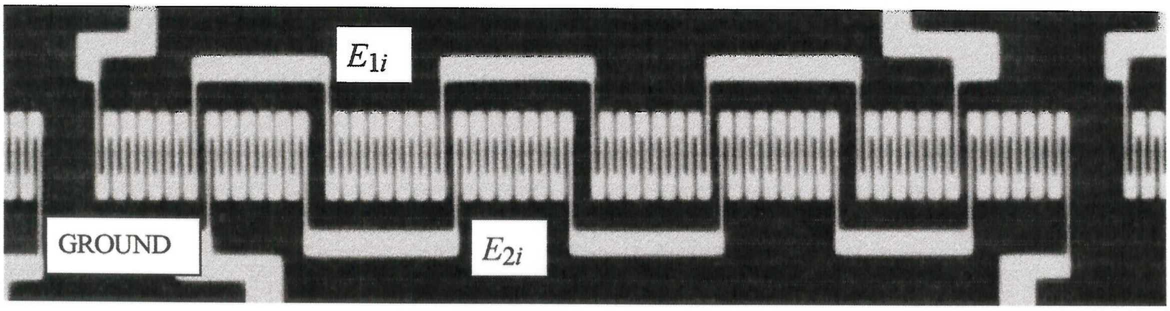

Fig. 1: Photograph of mode converter electrode pair in $LiNbO_3$ PMD equalizer

Experiment: A ~93 mm long distributed PMD compensator chip was fabricated with 73 cascaded mode converters of ~1.25 mm length each, one of which is shown in Fig. 1. Efficiency was ~250 V·mm for full conversion, and voltages of ±≤68 V were applied. Insertion loss was 6.9 dB including one connector, with a ±0.6 dB variation depending on polarization. Packaged chip and voltage sources form a compact unit. It was cascaded with a similar unit containing a somewhat shorter chip. 246 voltages in total were used to control this PMD equalizer with a combined DGD of 43 ps. The calculated and measured conversion bandwidth of individual converters was about 3 THz. If less than this optical bandwidth is needed neighbouring electrodes can be connected in parallel. This should considerably reduce the electronical effort and increase control speed at the same time. Thermal tuning is possible with a rate of ~100 GHz/K.

The PMD compensator is part of a 20Gb/s transmission system [7] (Fig. 2). A wavelength of 1565 nm was chosen. Two polarization-maintaining fiber pieces of 20 and 10 ps DGD, separated by motorized fiberoptic waveplates rotating at different speeds simulated the PMD of a fiber link. For PMD penalty

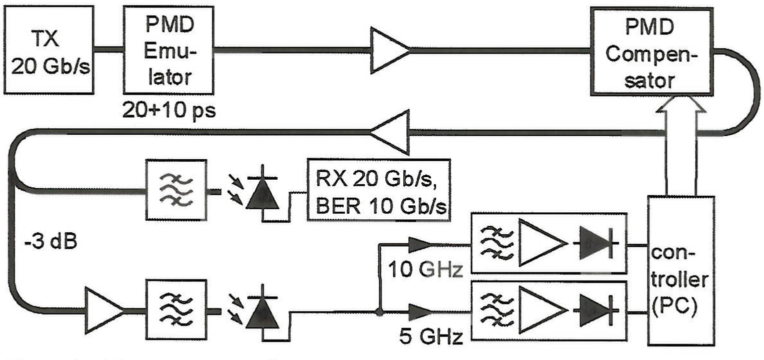

Fig. 2: Experimental setup

extraction the amplified photodetected signal was detected and fed into bandpass filters with 10 and 5 GHz center frequencies, and associated amplifiers and power detectors [4]. For convenience this was separate from the main receiver. BER was measured on one out of two 10 Gb/s data streams. A PC worked as a controller. The measured response time for full adaptation to a required compensation scenario was ~50 ms. While this figure is satisfactory for the moment we expect it can be improved.

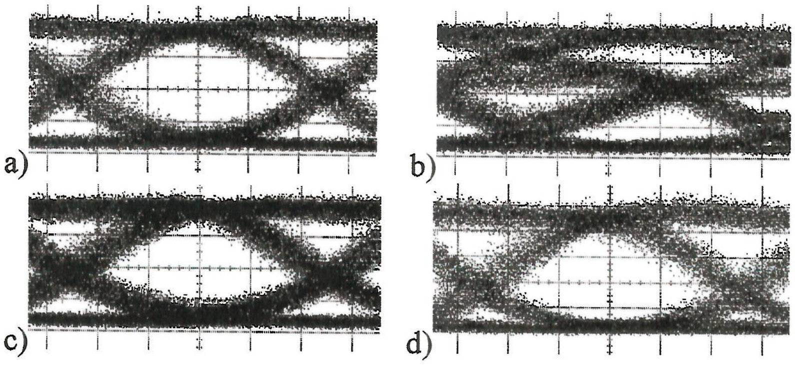

Fig. 3: Eye diagrams back-to-back (a), with emulator and switched-off compensator (b), with emulator and working compensator (c), with compensator alone (d)

The back-to-back eye diagram is shown in Fig. 3a. When PMD emulator and the switched-off compensator was in place the eye was usually closed (example: Fig. 3b). With PMD equalizer working the eye was again well opened (Fig. 3c). The equalizer was also able to produce a good eye pattern when the PMD emulator was removed (Fig. 3d). The power was set to correspond to an BER of $\sim 10^{-8}$ and the BER was recorded as a function of time while the emulator with rotating fiber loops was in place. Stable operation was observed unless the equalizer was switched off (Fig. 4). Time constraints prevented any further measurement at this point. However, due to its many electrodes and large optical bandwidth we expect the equalizer can operate also at higher bit rates.

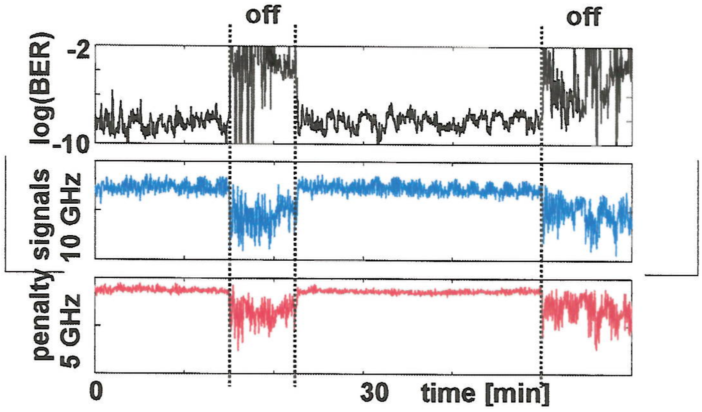

Fig. 4: Measured BER (top) and power spectral densities at 10 (middle) and 5 GHz (bottom) while fiberoptic waveplates rotate in the PMD emulator

Conclusions: A distributed PMD equalizer with a combined DGD of 43 ps in X-cut, Y-propagation $LiNbO_3$ has been realized and operated in a 20Gb/s transmission system. Accurate and fast compensation of up to 30 ps of differential group delay has been demonstrated.

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