Adaptive Polarization Mode Dispersion Compensation at 40Gb/s with Integrated Optical Finite Impulse Response (FIR) Filters

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Introduction

The increase in capacity in optical networks is realized by an increasing number of wavelength division multiplex (WDM) channels and an increase in the per channel bit rate. Today's optical transmission systems operate up to 40Gb/s per channel and higher bit rates are under research. With increasing bit rates physical fiber properties lead to serious signal distortions. Limiting effects arise due to changes in the birefringence and nonlinear fiber effects and cause pulse broadening. A residual birefringence between the both orthogonal polarization modes causes polarization mode dispersion (PMD), which has a statistical nature and is varying with time and frequency. Since bit rates exceed 10Gb/s, PMD becomes a limiting effect and gets more and more serious with higher bit rates. Therefore to guarantee a high performance transmission with low system outage probability PMD has to be compensated with an adaptive equalizer concept.
The adaptive polarization mode dispersion compensation with integrated optical finite impulse response (FIR) filters is based on the equalization of both orthogonal polarization modes by different transfer functions. This can be implemented by two individual optical FIR-filters or more compact by a single one designed in lattice structure, which can be integrated by cascading symmetrical and asymmetrical Mach-Zehnder Interferometer (MZI) in a planar light wave circuit (PLC) /1/. A gradient algorithm adopted from digital signal processing controls the filter coefficients to minimize the intersymbol interference (ISI) and maximize the eye opening. Additionally, with this setup it is possible to compensate for distortions due to chromatic dispersion (GVD), self-phase modulation (SPM) and group delay ripple (GDR) at the same time /2,3/.

Polarization mode dispersion theory

Polarization effects in single mode fibers can be described by the superposition of two orthogonal polarized HE_{11} modes, the polarization modes. In an ideal fiber both polarization modes have the same transmission properties. In contrast to an ideal fiber, real fibers show local birefringence caused by asymmetries in the fiber core geometry and mechanical stress, which may be intrinsic in the fiber and from extrinsic sources. The intrinsic perturbations result from imperfections during the manufacturing process and are permanent features of the fiber while extrinsic stress changes with time. The loss of the circular core geometry leads to different group velocities of the orthogonal polarization modes and results in pulse broadening, the polarization mode dispersion. The different group velocities can be modeled by different propagation constants $(\beta_{slow}, \beta_{fast})$ or refractive indices (n_{slow}, n_{fast}) for the slow and fast polarization modes:

$$\beta_{slow} - \beta_{fast} = \frac{2\pi f n_{slow}}{c} - \frac{2\pi f n_{fast}}{c} = \frac{2\pi f \Delta n}{c} \tag{1}$$

Changes of the birefringence axes along the fiber span and extrinsic stress lead to polarization mode coupling, which is a power coupling between the polarization modes. Polarization mode coupling is intrinsic due to the manufacturing process or extrinsic due to splices and bends or twists.
The birefringence of a fiber is changing over time because of changes in the ambient environment like temperature variations and mechanical distortions, therefore PMD is of statistical nature. In fibers with a lot of polarization mode coupling, i.e. for fiber length L≥2km, the polarization effects do not accumulate linearly but in a square root dependence on the fiber length. The reason is that PMD in long fiber spans accumulates randomly, as the influence of one fiber section may add or subtract from the next one, /4/.

$$PMD = D_{PMD}\sqrt{L} \tag{2}$$

The fiber is characterized by the PMD-coefficient D_{PMD} with the unit $(ps/\sqrt{km})$, which describes the $\sqrt{L}$ dependence. In installed fiber the PMD-coefficient varies between $D_{PMD}=0.1ps/\sqrt{km}$ for new fibers and $D_{PMD}=1ps/\sqrt{km}$ for old ones, but in some spans even higher coefficients may occur.

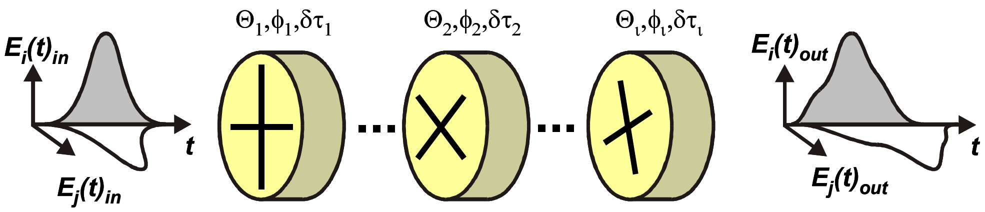

Figure 1: Schematic of the Waveplate-Model (angle of the birefringence axis Θ_i, phase ϕ_i, group delay difference $\delta\tau_i$)

To model the described PMD properties, the fiber is divided into a large number of birefringent segments or waveplates. Each of the segments induces a group velocity difference $\delta\tau$ between the orthogonal polarization modes. The change of the birefringence axis from segment to segment is modeled by rotating the waveplates and results in polarization mode coupling at the transition from waveplate to waveplate, Θ_i is the rotation angle. The phase shift ϕ_i denotes the transformation from linear to circular or elliptic polarized light. The model is named 'waveplate-model' and the transition of light in concatenated birefringent segments is a product of unitary Jones matrices /5,6,7/.

$$\vec{E}_{out}(\omega) = R_{N+1}\left(\prod_{i=1}^{N} R_i \Lambda_i(\omega) R_i^{-1}\right)\cdot \vec{E}_{in}(\omega) \tag{3}$$

$\vec{E}(\omega)$ is the electric field vector , the rotation matrix R_i characterizes the polarization mode coupling:

$$R_i = \begin{bmatrix} \cos(\Theta_i) & \sin(\Theta_i) \\ -\sin(\Theta_i) & \cos(\Theta_i) \end{bmatrix} \tag{4}$$

The different group velocities and the carrier frequency phase shift between the polarization modes are described by a diagonal delay matrix:

$$\Lambda_i = \begin{bmatrix} e^{j\left(2\pi f \frac{\delta\tau_i}{2} + \frac{\phi_i}{2}\right)} & 0 \\ 0 & e^{-j\left(2\pi f \frac{\delta\tau_i}{2} + \frac{\phi_i}{2}\right)} \end{bmatrix} \tag{5}$$

with $\delta\tau_i = \frac{2\pi f \Delta n}{c} \cdot \delta L$, δL= *segment length.*

For modeling the statistical nature of PMD either a lot of realizations with varying rotation angles and phase shifts at a fixed carrier frequency or varying carrier frequencies with fixed rotation angles and phase shifts can be simulated. For a real fiber implementation the minimum number of waveplates has to be $n=12$, the rotation angles and carrier frequency phase shifts have to be uniformly distributed in $(0,2\pi]$, /8/.

Besides the PMD-coefficient to characterize the PMD-properties of the fiber the differential group delay (DGD, $\Delta\tau$) is widely used /9,10/. The DGD is the difference of the group delay between the principal states of polarization (PSOP). Considering a PMD-fiber, the output polarization state $\overrightarrow{pol_{out}}$ depends on the input polarization $\overrightarrow{pol_{in}}$ and the optical frequency f. The PSOP are those 2 polarization states that are to first order frequency independent.

$$\frac{d}{df}\overrightarrow{pol}_{out}\left(f,\vec{\Omega}\right) = 0 \tag{6}$$

with
$$\vec{\Omega}(f) = \Delta\tau(f) \cdot \overrightarrow{s(f)}$$

describing the PMD-vector, $\vec{s}$ is the stokes vector.

To analyze the frequency dependence of the PMD vector, it is expanded into a Taylor series, the dot '•' denotes the frequency derivative:

$$\vec{\Omega}(f) = \underbrace{\vec{\Omega}(f_0)}_{1^{st}\,order} + \underbrace{\dot{\vec{\Omega}}(f-f_0)}_{2^{nd}\,order} + \frac{1}{2}\ddot{\vec{\Omega}}(f-f_0)^2 + \cdots \tag{7}$$

PMD of 1st order is defined by $\vec{\Omega}(f_0)$. The direction of the vector is the slow axis of the PSOPs, the length of the vector is the DGD

$$\left|\vec{\Omega}\right| = \Delta\tau, \tag{8}$$

The simulation results for a fiber span of $L=100km$ and a PMD coefficient of $D_{PMD}=1ps/\sqrt{km}$ and a sufficient number of waveplates are shown in Fig. 2. Figure 2a shows the frequency dependence of the DGD, Fig. 2b the Maxwellian distribution of the DGD.

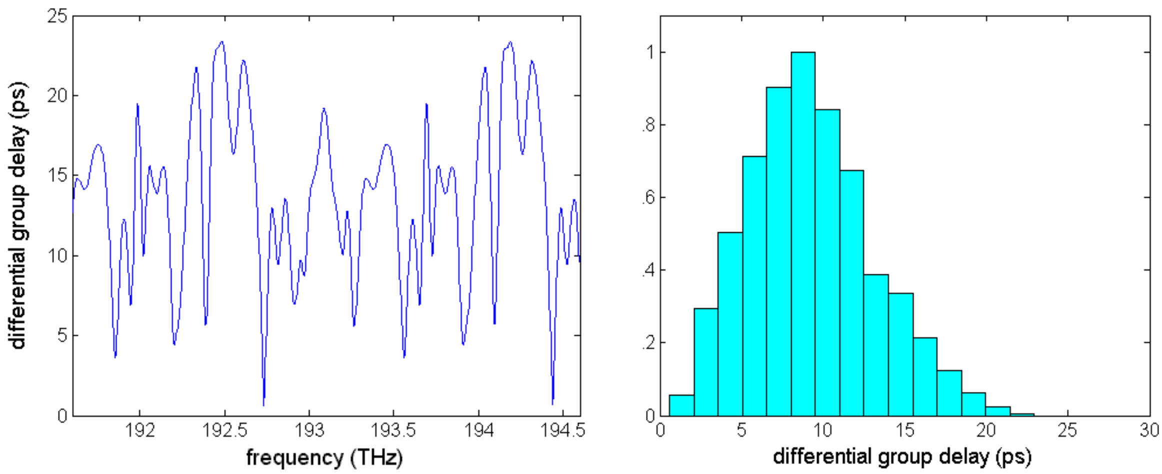

Figure 2: Frequency dependence and Maxwellian distribution of the DGD for a simulated fiber span of $L=100km$ and $D_{PMD}=1ps/\sqrt{km}$

Second order PMD is characterized by the first derivative of the PMD-vector:

$$\left|\dot{\vec{\Omega}}\right| = \left|\frac{d\Omega}{df}\right| = \left|\frac{d\Delta\tau}{df}\cdot\vec{s} + \Delta\tau\cdot\frac{d\vec{s}}{df}\right| = \tau_{\omega} \qquad (9)$$

The derivative of the DGD $d\Delta\tau/df$ denotes the frequency dependency, the derivative of the stokes vector ds/df describes the depolarization due to the rotation of the PSOP.
The frequency dependence of the PMD even in the signal bandwidth range makes it necessary for a proper analysis to take into account the frequency independent 1st order PMD as well as the frequency dependent higher order terms of the PMD-vector. Therefore bandwidth efficient modulation formats such as duobinary transmission may be a solution to reduce the influence of higher order PMD in comparison to conventional NRZ or RZ coding /11/. However, PMD is of statistical nature and the induced signal distortions are changing with time and frequency. The ITU recommends a maximum system outage probability of $P_{outage}=5.7\cdot10^{-5}$ which corresponds to *30 min/year* and results in a maximum mean PMD of 10% of the bit rate, e.g. $PMD_{max,10Gb/s}=10ps$, $PMD_{max,40Gb/s}=2.5ps$. To guaranty the recommended or an even better outage probability adaptive PMD compensation is necessary, especially for high bit rates, long fiber spans and old fibers with a high PMD-coefficient.

Polarization mode dispersion compensation

Existing PMD compensation concepts can be divided into 2 classes: electrical and optical equalization. PMD equalization in the electrical domain is based on a least mean square criterion to minimize the intersymbol interference (ISI) by feedforward equalization (FFE), decision feedback equalization (DFE) or maximum-likelihood sequence estimation (MLSE) /12,13/. Performance limitations arise due to the envelope demodulation of the photo diode. All these equalizers exhibit a penalty pole, when the power splitting into the PSOP is equal and the DGD is close to, or higher than the bit period. An implementation

for bit rates of more than *10Gb/s* is not available at the moment because of limitations in high speed electronics.
The optical equalizers are not limited by the bit rate. A practical optical PMD compensation approach is to build the inverse system of the PMD in front of the receiver to equalize the accumulated PMD of the fiber span, as described in Fig. 3a. A 1st order PMD compensator needs a polarization control and a variable delay line to compensate for the DGD, Fig. 3b. For compensating PMD of 1st and higher order the fiber has to be rebuild in analogy to the waveplate model. Cascaded polarization controllers and birefringent segments, e.g. polarization maintaining fiber or photonic crystals, model the polarization mode coupling and DGD between the PSOP, Fig. 3b. This approach could only compensate for PMD. The PMD compensator may be driven by e.g. time or frequency domain equalization criteria or the degree of polarization, /14,15/.

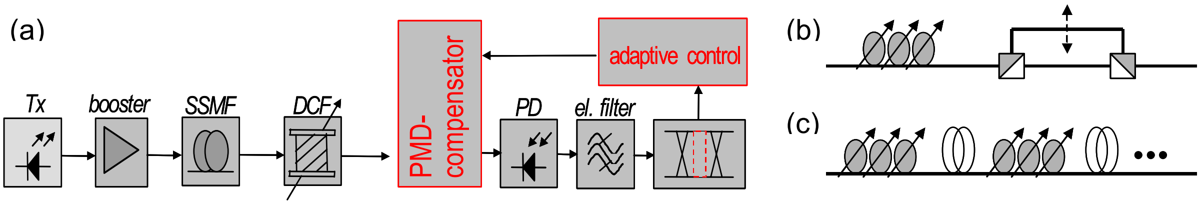

Figure 3: Schematic of a PMD compensator setup (a), 1st order PMD compensator (b), 1st and higher order PMD compensator (c)

The PMD compensation concept with optical FIR-filters does not build the inverse system. The filter operates in front of the receiver as well, a gradient algorithm adopted from electrical signal processing controls the filter coefficients for a minimum of ISI and a maximum eye opening. Therefore it is not only possible to compensate for PMD but also for other distortions like GVD, SPM and GDR, /2,3/.
A common implementation of an optical FIR-filter with variable coefficients for an adaptive control is a structure of cascaded symmetrical and asymmetrical MZI, which can be easily integrated as a planar lightwave circuit (PLC), /1/. The symmetrical MZI form variable couplers, the asymmetrical MZI form the delay lines. The frequency periodicity of the filter, the free spectral range (FSR), is given by the inverse of the delay, $FSR=1/T_d$. The filter order N is the number of cascaded delay lines. By integrating a phase shift element in the delay arms it is possible to realize complex coefficients.

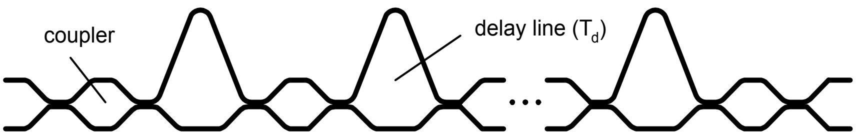

Figure 4: Cascaded Mach-Zehnder Interferometer filter structure

While equalizing effects which are polarization independent such as GVD or SPM, only a single input and output of the filter structure is used. The PMD compensation concept needs a different transfer function for both polarization modes. One solution is to use a polarization beam splitter at the input of the filter and feed each input with one of the orthogonal polarizations (single filter setup, Fig. 5a). In this case each polarization is filtered by a different transfer function, but not independent of each other. By using separate filters for the orthogonal polarizations independent tunable transfer functions can be implemented (double filter setup, Fig. 5b), but the complexity is doubled.

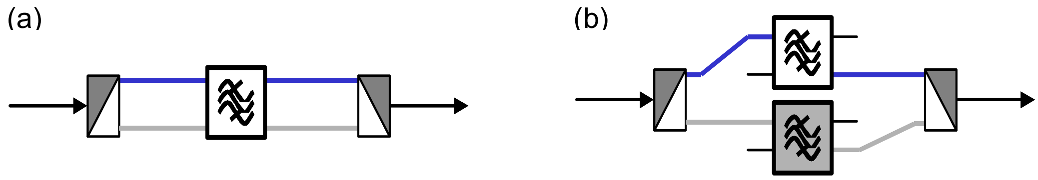

Figure 5: PMD compensation concept with integrated optical FIR-filter: single filter setup (a), double filter setup (b)

Compensation of 1st order PMD

For emulating 1st order PMD the waveplate model is reduced to a single rotating waveplate. The angle between the polarization modes of the input light and the birefringent axis of the waveplate determines the power splitting γ between the PSOP. The worst case, equal power in the PSOP and a DGD of the bit length or more, causes a closed eye pattern with zero eye opening. By integrating a polarization control in front of the polarization beam splitter, the filter function is comparable to a variable delay line. The equalization performance at 40Gb/s for a NRZ coded signal and an optical FIR-filter of a FSR=100GHz and order $N=2$ is shown in Fig. 6 and 7. The single filter (6a) and the double filter (6b) setup are compared for different power splitting ratios γ=0.1…0.5 and a DGD up to 25ps.

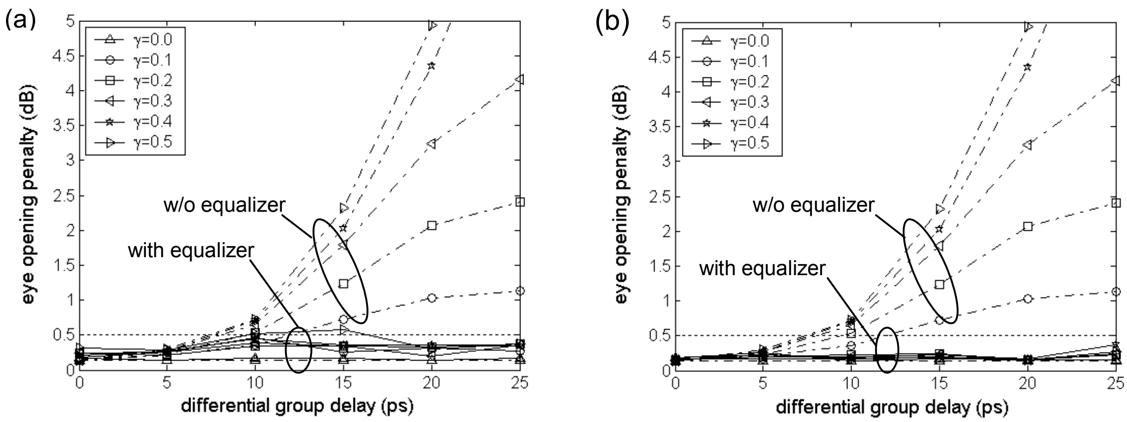

Figure 6: 1st order PMD compensation at 40Gb/s: single filter setup (a) and double filter setup (b)

In both setups the eye opening penalty (EOP) is reduced below EOP=0.5dB. Even in the worst case (γ=0.5, DGD=25ps) the equalized eye pattern diagrams show a clear and wide eye opening, Fig 7. The equalization results of the double filter setup with two independent different transfer functions for the polarization modes and those of the single filter setup with two dependent transfer functions are nearly comparable, there is just a slight difference. The ideal compensation of 1st order PMD is possible if the length of the impulse response of the filter is at least as large as the DGD. Here the length of the Impulse response is $T=N\bullet T_d=20ps$. The DGD of 25ps can not be compensated in total and the EOP is increasing, Fig. 6b.

(a) (b) (c)

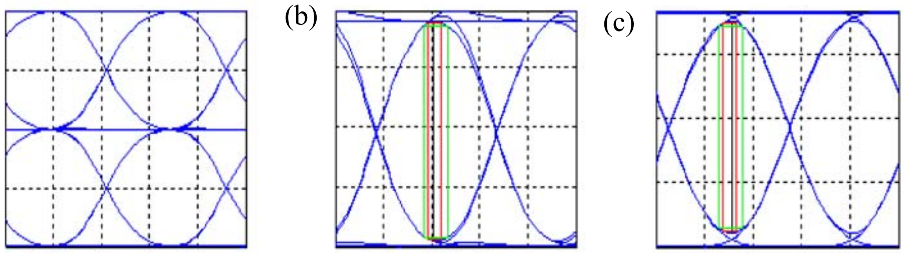

Figure 7: 1st order PMD worst case eye pattern: unequalized (a), equalized single (b) and double (c) filter setup

Compensation of 1st and higher order PMD

For demonstrating the capabilities of the equalizer the mean PMD is chosen 4 times higher than the ITU recommendation for a maximum outage probability of 30 min/year. The PMD emulator for 1st and higher order PMD is based on the waveplate model with a mean PMD of 10ps as described in the previous section (L=100km, D_{PMD}=1ps/$\sqrt{km}$). The equalizer performance is evaluated for a 40Gb/s NRZ coded transmission. The DGD distribution is already shown in Fig. 2, the distribution of the EOP in Fig. 8. The comparison of both distributions shows that in the presence of higher order PMD, the DGD is not directly correlated with the EOP as it is for 1st order PMD. The EOP histogram is monotone decreasing with increasing EOP.

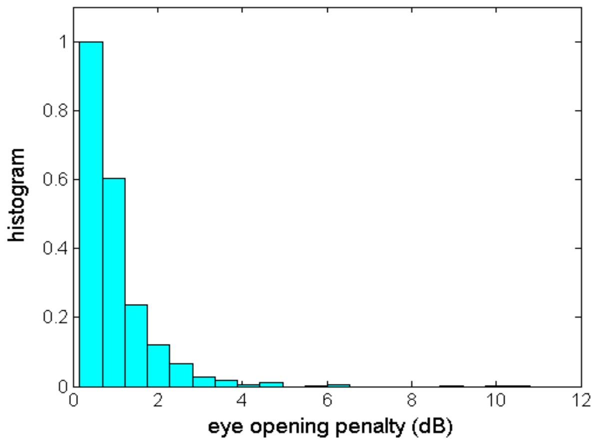

Figure 8: Eye opening penalty distribution at 40Gb/s for a fiber span of *L=100km*, a PMD coefficient of $D_{PMD}=1ps/\sqrt{km}$

The equalization results for the single and double filter setup are shown in Fig. 9. The EOP for the unequalized case is plotted versus the equalized case. The line with the slope of 1 denotes the zero equalization gain case. The shorter the distance to the bottom line of the lower triangle the better the equalization performance.

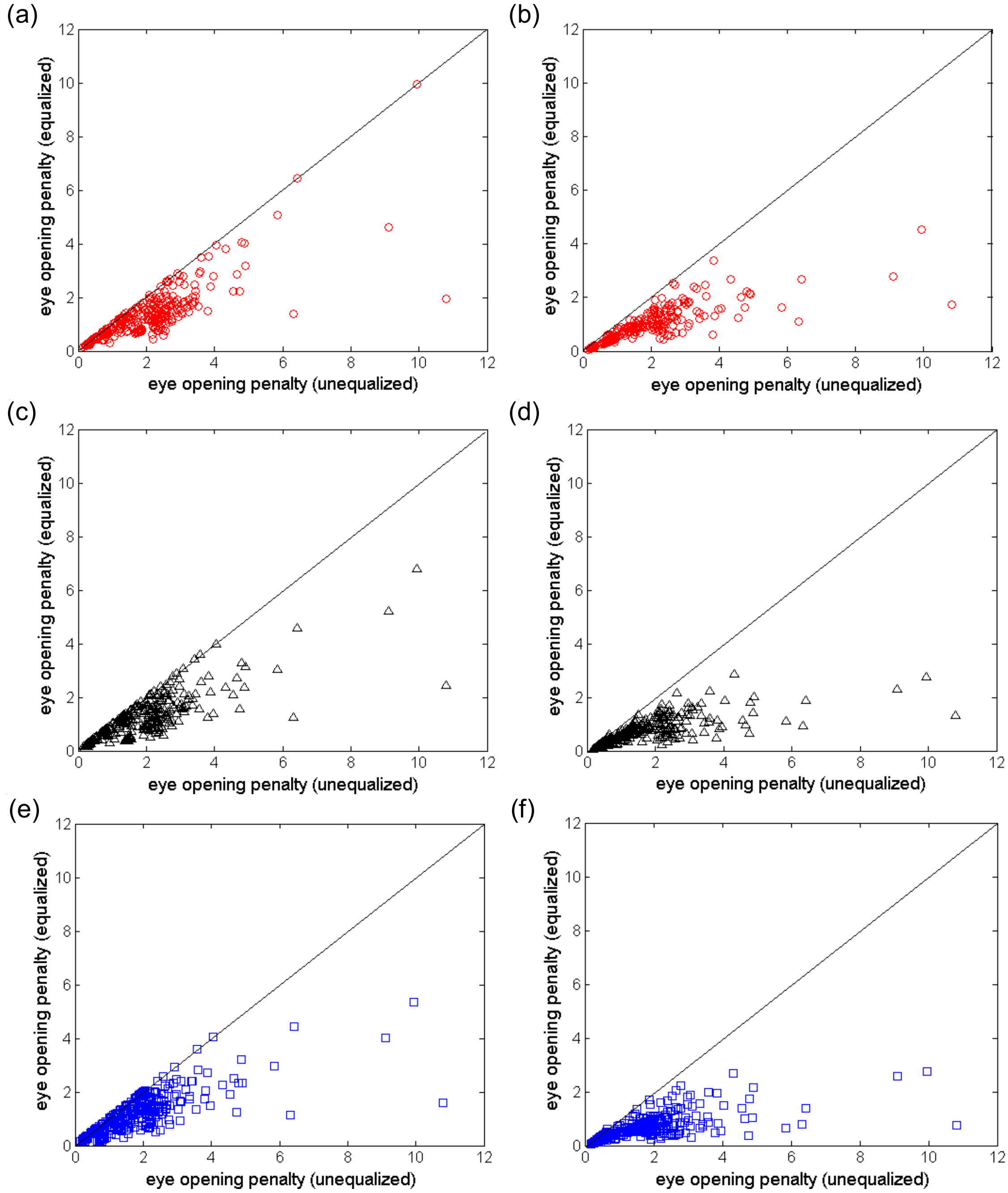

Figure 9: Equalization results at 40Gb/s for the single (a,c,e) and double (b,d,f) filter setup at different filter orders: n=2 (circle, top row), n=4 (triangle, middle), n=6 (square, bottom)

Both filter setups show an EOP improvement due to the equalizer of several dB, at high unequalized EOP a $\Delta EOP_{unequalized,\ equalized}$ up to 10dB. By increasing the filter order from $N=2$ up to $N=4$, there is a clear improvement in the EOP for both setups. Just a slight improvement from $N=4$ to $N=6$ indicates, that a filter order of $N=6$ is sufficient for the equalization of 1^{st} and higher order PMD with a mean PMD of 10ps.

If the filter transfer functions to equalize the polarization modes can be controlled independently as in the double filter setup, the performance is approximately by a factor of 2 better than the single filter setup with dependent transfer functions. Already for a low filter order of $N=4$ no EOP greater than 3dB occurs and the very most part is below 1dB, what is the criterion for the system outage probability.

Conclusion

By using a different transfer function for each polarization mode and an adaptive algorithm from digital signal processing to control the filter coefficients and minimize the ISI and eye opening, the PMD compensation concept with integrated optical FIR-filters is capable of reducing the system outage probability due to PMD of 1st and higher order. Besides the PMD compensation, optical FIR-filters are able to equalize GVD, SPM and GDR at the same time. Optical FIR filters with variable complex tap coefficients can easily be integrated as a PLC and packaged into a small and smart device with a lot of functionality.

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