# INTEGRATED OPTICAL FIR-FILTERS FOR ADAPTIVE EQUALIZATION OF FIBER CHANNEL IMPAIRMENTS AT 40GBIT/S

Marc Bohn[1,2], Werner Rosenkranz[2], Folkert Horst[3], Bert Jan Offrein[3], Gian-Luca Bona[3], Peter Krummmrich[4]

[1]*Siemens AG, Corporate Technology, Munich, Germany, marc.bohn@siemens.com;* [2]*University of Kiel, Chair for Communications, Germany, wr@tf.uni-kiel.de;* [3]*IBM Research GmbH, Zurich Laboratory, Switzerland, fho@zurich.ibm.com;* [4]*Siemens AG, ICN, Munich, Germany*

**Abstract:** In high bitrate optical transmission systems the dynamic changes of the transmission channel easily exceed the system tolerances for an error free operation. To meet the tolerances an adaptive equalizer is necessary. We demonstrate the capabilities of planar lightwave circuit integrated optical FIR-filters for an adaptive compensation of optical fiber channel impairments with electrical spectrum monitoring as feedback in simulations and measurements at 40Gb/s.

**Key words:** optical communications; optical filter; optical equalizer; FIR-filter; planar lightwave circuit; adaptive equalization; dispersion compensation; PMD compensation

## 1. INTRODUCTION

The adaptive distortion compensation of fiber channel impairments in current and next generation high speed optical transmission systems is of high interest. With increasing bitrates and increasing complexity of the optical layer, signal distortions are increasing, while the tolerances of the system are decreasing. The dynamic changes of the transmission channel due to chromatic dispersion (CD), polarization mode dispersion (PMD) and nonlinear distortions, such as self-phase modulation (SPM), easily exceed the tolerable amount for an error free operation of the transmission system. To compensate for these time and frequency varying distortions and to meet the system tolerances, a static compensation approach is not sufficient anymore and an adaptive solution for equalization is necessary.

Adaptive equalization schemes exist in the electrical and in the optical domain. The electrical equalizers operate behind the opto-electrical conversion. Due to the envelope demodulation of the photo diode, the carrier and phase information get lost. Implemented filter structures are finite impulse response (FIR) and decision feedback (DF)[1] equalizers operating up to a bitrate of *10Gb/s*. A new approach is maximum likelihood sequence estimation (MLSE)[2], but not yet implemented for high bitrates.

Optical equalizers have advantages in comparison to electrical ones, as they are not bitrate limited due to the electronics and operate in front of the nonlinear photodiode. Reported adaptive optical equalization experiments compensate either for chromatic dispersion or polarization mode dispersion by devices that model the inverse system, e.g. CD compensation by fiber bragg gratings (FBG) and etalons or PMD compensation by cascaded polarization control and birefringent elements[3-6].

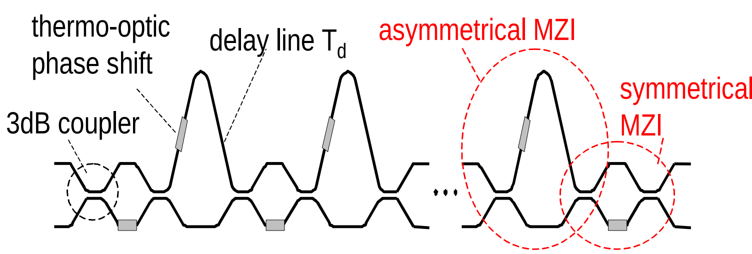


*Figure 1.* Schematic structure of an integrated optical FIR-lattice filter: cascaded symmetrical and asymmetrical Mach-Zehnder Interferometers (MZI)

Within our approach, a planar lightwave circuit (PLC) integrated optical FIR-filter offers a large variability in compensating for distorting effects. These filter structures have variable complex coefficients and the transfer function can be arbitrarily tuned. Not only a single fiber impairment e.g. CD, SPM, or PMD can be compensated for, but also combinations of all these distortions[7-9]. In addition, optical FIR-filters have a periodic frequency response and tunable center wavelength. By matching the frequency response periodicity (i.e. the free spectral range (FSR)) to the channel grid, a single filter can equalize a number of WDM channels simultaneously. An efficient way of implementation is a lattice filter, which consists of cascaded symmetrical and asymmetrical Mach-Zehnder Interferometers (MZI), Fig.1.

The device we used for the experiments is a $6^{th}$ order lattice filter with a *FSR=100GHz*. It it designed and fabricated using the IBM high-index-contrast SiON technology[10]. The die size is $16 \times 12$ *mm*.

Apart from the equalizer itself, a feedback signal for the automatic adaptation is necessary. Criteria for the adaptive control have been proposed in the time as well as in the frequency domain, e.g. eye opening, Q-factor, bit error rate or intersymbol interference and vestigial side band filtering, narrow optical filtering, monitoring a subcarrier, the clock intensity or the electrical spectrum[7-9,11-15].

In the time domain the classical adaptive equalization scheme in communication theory, the minimization of the intersymbol interference (ISI) with a Least Mean Square (LMS) error algorithm is a promising approach[7]. But the ISI generation is problematic at high bitrates and not yet implemented.

To demonstrate the adaptive capabilities of the optical FIR-filter, we choose electrical spectrum monitoring as adaptive feedback for simultaneous CD and PMD compensation, because of its sensitivity to both, good correlation to the signal distortions, simplicity and ease of implementation[8,9].

## 2. ADAPTIVE COMPENSATION OF CD AND PMD WITH ELECTRICAL SPECTRUM MONITORING AS FEEDBACK SIGNAL

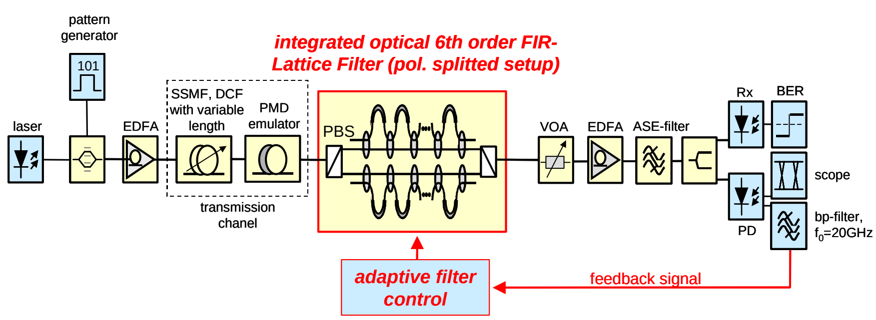


*Figure 2.* System setup: adaptive equalization with optical FIR-filters and electrical spectrum monitoring. When compensating for PMD, this polarization splitted setup is necessary. Each polarization is equalized with a separate filter. For CD compensation, a single filter without polarization splitting is sufficient.

In contrast to the time and optical frequency domain criteria, adaptive feedback solutions within the electrical spectrum are fast, inexpensive and easy to implement by electrical bandpass filters and power monitoring. We demonstrate a strategy of monitoring a single frequency for combined adaptive CD and PMD compensation in a *40Gb/s NRZ* transmission setup, Fig.2.

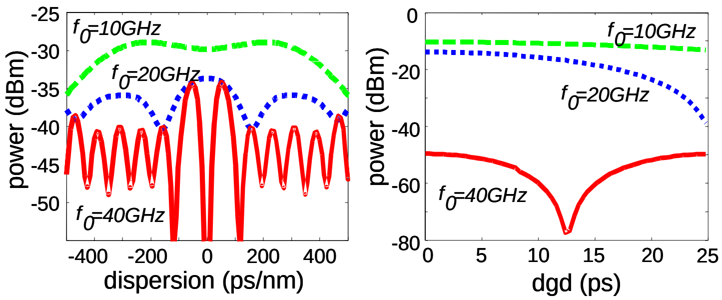


*Figure 3.* Power response of the received bandpass filtered electrical signal for distortions due to CD (left) and PMD (right) at *40Gb/s*

Signal distortions are determined through changes of the transfer function of the optical fiber. The optical fiber transfer function is reflected in the power spectral density or the electrical spectrum of the received signal. Monitoring the power of the bandpass filtered received electrical signal for various dispersion values results in an oscillating characteristic with a global maximum ($f_0<f_{bit}$) or minimum ($f_0=f_{bit}$) at zero chromatic dispersion for linear transmission, Fig.3(left). The bandpass filtered electrical PMD signal has well defined alternating power maxima and minima at a differential group delay (DGD) of e.g. n-times $T_{bit}/2$ for a center frequency of $f_0=40GHz$, Fig.3(right).

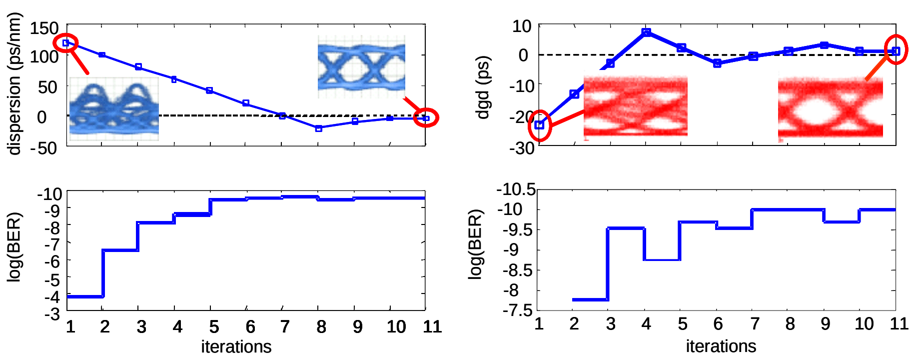


*Figure 4.* Adaptive compensation results: residual CD of the transmission channel & equalizer, eye patter, BER(left); residual DGD of the transmission channel & equalizer, eye patter, BER(right)

For a unique adaptive solution, the feedback signal has to be strictly monotone increasing or decreasing up to the point of minimal signal distortion. Therefore the operation range of the power response of the bandpass filtered electrical signal depends on the bandpass filter center frequency $f_0$, e.g. $D=\pm180ps/nm$ or $DGD=25ps$ for $f_0=20GHz$. The operation range is increasing with decreasing center frequencies. But the center frequency should be chosen as large as possible, because the steepness of the power response and the adaptation speed is decreasing with smaller center frequencies.

The adaptive compensation of CD and PMD, respectively, using the feedback signal generated by an electrical bandpass filter with a center frequency $f_0=20GHz$ is demonstrated in two experiments, Fig.4(left and right).

From a starting point of approximately $D=120ps/nm$ residual dispersion ($BER<10^{-4}$) at the receiver, the adaptive control algorithm varies the residual dispersion of the equalizer until the optimum CD value is reached. For CD compensation only, a single filter is sufficient. The polarizations do not have to be splitted as indicated in Fig.2. In a few iteration steps the eye pattern diagram is well opened, the bit error rate reduced and the dispersion compensated.

For PMD compensation, the orthogonal polarization modes have to be splitted, each polarization equalized by a separate filter and the polarizations combined (polarization splitted setup), see Fig.2. The starting point is a DGD value of *23ps* at the receiver. The adaptive equalizer compensates for the DGD in a few iteration steps, the eye pattern diagram is well opened, the bit error rate reduced.

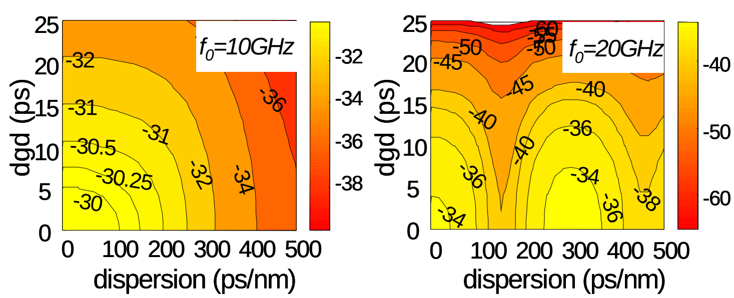


*Figure 5.* Power response of the received bandpass filtered electrical signal for distortions due to CD and PMD at 40Gb/s: bandpass center frequency $f_0=10GHz$ (left), $f_0=20GHz$ (right)

For the combination of both signal distortions, PMD and CD, the bandpass filtered electrical signal power is a two dimensional function depending on the amount of CD and DGD with a global maximum at zero

CD and DGD, Fig.5. Therefore, electrical spectrum monitoring can be used to compensate for CD and DGD simultaneously. The simultaneous equalization of CD and PMD is shown experimentally, Fig.6, and by simulations, Fig.7.

In the measurement the transmission channel is set in a first step to a GVD value of *100ps/nm*. While compensating for GVD only, a sensitivity gain of *4.5dB* and a sensitivity penalty of less than *1dB* in comparison to the back to back case at a $BER=10^{-9}$ is measured. Next, a PMD setting of the transmission channel of *DGD=25ps* is compensated. The initially closed eye pattern is clearly opened and the resulting sensitivity penalty is approximately *1dB*. Finally the transmission channel is set to GVD and PMD values of *GVD=100ps/nm* and *DGD=25ps*. Equalizing the combination of PMD and GVD, the completely closed eye pattern is clearly opened and the sensitivity penalty is less than *1.5dB*.

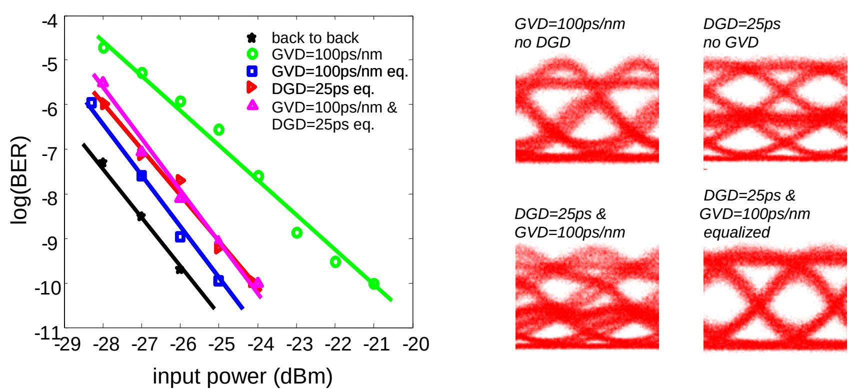


*Figure 6.* Measurements results of simultaneous CD and PMD compensation: (left) BER, (right) eye pattern diagrams

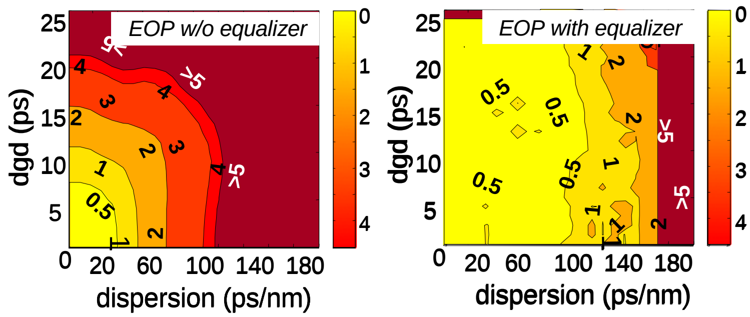


*Figure 7.* Simulation results of simultaneous CD and PMD compensation: (left) w/o equalizer, (right) with adaptive equalizer

The limits of this setup can be demonstrated by looking at the simulated eye opening penalties (EOP). The characteristic *1dB* EOP line is increased from *D=60ps/nm* and *DGD=12ps* without equalizer up to *D=140ps/nm* and *DGD=24ps* with equalizer. Exceeding the operation range leads the adaptive algorithm to converge into a local maximum. To increase the operation range, the bandpass filter frequency has to be decreased or combined with a bandpass filters of lower center frequency. For better equalization results inside the adaptation region, the filter order has to be increased.

## 3. CONCLUSION

PLC integrated optical FIR-filters structures are a promising optical device to adaptively compensate for a single or combinations of several fiber channel impairments. The footprint is very small, and the filter coefficients, i.e the transfer function, can be fast and easily tuned by the thermo-optic effect. Electrical spectrum monitoring is a powerful, robust, fast and easy to implement solution for the adaptive feedback with a good correlation to signal distortions due to CD and PMD. Additional distortions due to SPM or chirp will be compensated by balancing the impact of SMP and residual CD into an optimum.

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