An Adaptive Optical Equalizer Concept for Single Channel Distortion Compensation

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Abstract: We present a new adaptive optical equalizer concept for single-channel distortion compensation and analyze the performance of an adaptive optical FIR-filter in lattice structure (cascaded MZI) with respect to equalization of residual dispersion, self-phase modulation and polarization-mode dispersion.

Introduction

In high bitrate optical transmission systems signal distortion due to dynamic changes of the transmission channel need adaptive equalization. The most challenging problems at the moment are variations of group velocity dispersion (GVD) and polarization mode dispersion (PMD) resulting from changes in the ambient environment.

Existing concepts can be divided into two classes: electrical equalization of GVD, self phase modulation (SPM) and PMD /1,2/. Here performance limitations arise due to the envelope demodulation in the photodiode. The 2nd class of adaptive equalizers are optical approaches, which basicly compensate for only one fiber impairment /3,4/. We combine adaptive GVD, SPM and PMD compensation in one optical device.

The filter concept is based on a lattice structure, which can be integrated by cascading symmetrical and asymmetrical Mach-Zehnder Interferometer (MZI) in a Planar Lightwave Circuit (PLC) /5/. In this structure (see Fig.1) the symmetrical MZI acts as directional coupler, the asymmetrical as delay and phase shift element. It is possible to realize finite impulse response (FIR) and by including feedback paths (ring resonators), infinite impulse response filters (IIR) /6/. Because of the feedback paths IIR filter generally provide at equal filter order better equalization results than FIR filter, but are more difficult to realize.

Up to now optical FIR- and IIR filters for dispersion and PMD compensation are designed by modeling the inverse system /3,7/. We use an adaptive algorithm adopted from digital signal processing and electrical eye analysis to control the filter coefficients and maximize the eye opening. The applied algorithm provides maximum flexibility regarding the joined compensation of all kinds of single-channel distortions with one single filter. By integrating this device into the receiver we obtain excellent dispersion tolerance, SPM and PMD compensation.

System

In order to evaluate the system performance of the adaptive optical equalizer concept, the following setup is used, see Fig. 1. The transmitter provides a *40 Gbit/s NRZ* signal at $\lambda=1550nm$. Various free spectral ranges (FSR) and launch power levels are regarded: the linear case for dispersion and PMD compensation, as well as the nonlinear case ($P_{in}=10dBm,\ 12dBm$) for additional SPM equalization. $L=100km$ standard single mode fiber (SSMF) ($\gamma=1.54\ 1/Wkm,\ \alpha=0.22dB/km$) are followed by a dispersion compensating fiber (DCF) module to tune a certain range of accumulated dispersion at the receiver input. The receiver consists of the adaptive optical filter, a photodiode (square law detection), a low pass filter (*bessel filter 3rd order,* $f_{3dB}=28GHz$) and an eye analysis.

The optical filter is simulated according to the hardware realization as a FIR filter up to 10th order in lattice structure with uniform tap spacings ($\Delta T=12.5,\ 10,\ 5,\ 2.5ps$), which results in a free spectral range $FSR=1/\Delta T=80,\ 100,\ 200,\ 400GHz$. The tap weights are set by the adaptive control algorithm. The adaptive algorithm is based on nonlinear optimization and uses the minimization of Intersymbol Interference (ISI) and maximization of the eye opening as optimization criterion. The criterion is formulated as a nonlinear least squares problem. Common algorithms to solve this problem /8/ are the modified Gauss-Newton Methods and the Levenberg-Marquardt Method. Our simulations show, that the Levenberg-Marquardt Method provides the better and more stable results.

Results and Discussion

We evaluate the filter performance by simulating the dispersion tolerance, SPM and PMD equalization of the adaptive optical filter concept, for different FSRs and input power levels.

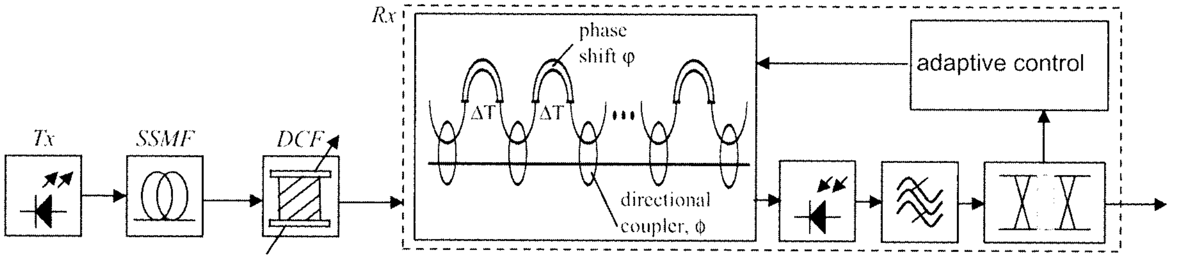

Fig. 1: System setup, evaluation of the adaptive optical equalizer performance

The goal is to achieve maximum equalization of the distorted signal at minimum cost. Besides the tap weights, the tap spacing and the filter order has to be optimized, which results in a certain length of influence and granularity of the filter. In our analysis the maximum filter order is set to $n=10$, which allows moderate size and attenuation in a realization by means of PLC technology.

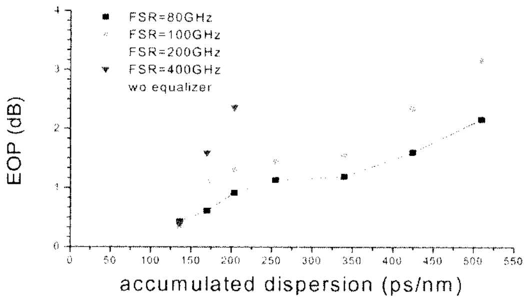

Fig. 2: EOP due to accumulated dispersion @ 40Gb/s w/o equalization and with optimized FIR filter 10th order

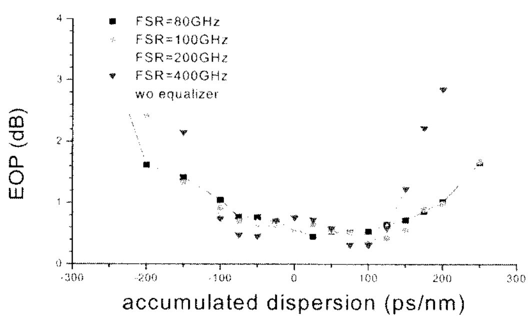

Fig. 3: EOP due to accumulated dispersion and SPM @ 40Gb/s w/o equalization and with optimized FIR filter 10th order

In the linear regime a standard receiver has a dispersion tolerance referenced to 1dB Eye Opening Penalty (EOP) of approximately $D=\pm 60 ps/nm$ at 40Gbit/s. Applying the adaptive concept, it is possible to extend the tolerance up to more than $D=\pm 200 ps/nm$ (400% !) if an optical equalizer of 10th order with an optimum FSR of $FSR=80GHz$ is used, see Fig. 2.

In the nonlinear regime, there is still excellent dispersion tolerance, but also SPM equalization. At a launch power $P_{in}=10dBm$ the dispersion tolerance for 1 dB EOP is in the range of $D=-100 \ldots +200 ps/nm$ accumulated dispersion and more than 0.5dB improvement through SPM equalization, see Fig.3. Generally a standard receiver without equalization has an EOP=1dB due to SPM already at $P_{in}=9dBm$. By including the adaptive filter, we realize a better performance up to more than $P_{in}=12dBm$, which results in an SPM improvement of 3 dB!

To get the most efficient equalizer performance, the length of influence of the filter (the impulse response) has to be chosen as long as possible. To realize this at minimum filter order, the filter bandwidth has to be chosen as small as possible, keeping in mind the signal bandwidth. The minimum FSR for optical filters to reach a sufficient bandwidth is between $FSR=2 \ldots 2.5 f_{bit}$, which corresponds to tap spacing of a T_{bit} / n, $n \geq 2$ equalizer. For a smaller bandwidth there is an additional penalty due to bandwidth narrowing. In case of a fixed number of coefficients a higher bandwidth results in smaller tap spacing, the granularity of the impulse response increases and the performance improves until the impulse response of the filter is shorter than the distorted pulse width.

PMD equalization is possible using the same setup as before (single-filter setup). However, a much better performance can be achieved by including a polarization beam split (PBS) to equalize each principal state of polarization (PSP) separately (double-filter setup). To evaluate the equalizer performance a filter order of $n=5$, $FSR=100GHz$, equal power in both PSP and varying mean differential group delay (DGD) are considered.

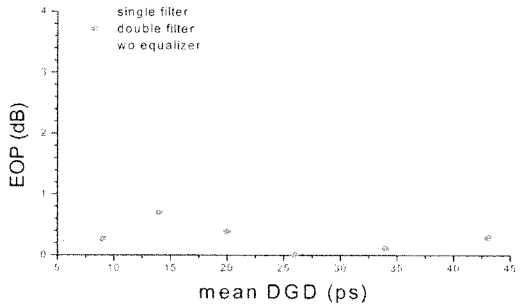

Fig. 4: EOP due to PMD @ 40Gb/s w/o equalization and with optimized FIR filter 5th order with and w/o PBS

Figure 4 shows the equalizing performance for the single- and double-filter setup. While the single filter has an increasing EOP with increasing DGD, the double filter stays below EOP=0.70dB. The first setup is not optimal, as each orthogonal mode has to be equalized seperately and has its 3dB limit at $DGD \approx T_{bit}$. The double filter setup controls each PSP seperately and the equalizing limit is increased to $DGD \approx n/FSR$, n=*filter order*, which is the length of the impulse response.

Conclusion

We demonstrated by simulations that one single optical FIR filter controlled by an adaptive algorithm based on eye analysis can act as an excellent universal equalizer for single-channel distortions, such as dispersion, SPM and PMD. The demonstrated equalizer performance and the concept of joined equalization of these fiber impairments with one single filter is a large improvement over the existing adaptive equalizer concepts.

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