Electronic Dispersion Precompensation With a 10-Gb/s Directly Modulated Laser

Stefan Warm, C.-A. Bunge, Torsten Wuth, and Klaus Petermann

Abstract—We present 10-Gb/s transmission with a directly modulated laser (DML) avoiding inline dispersion compensating by electronic precompensation. To apply this technique of electronic dispersion precompensation to DMLs, a new approach based on artificial neural networks will be introduced. We realized a transmission of 190-km standard single-mode fiber in a laboratory experiment. Simulations show that compensation of up to 350 km can be achieved.

Index Terms—Directly modulated laser (DML), dispersion compensation, electronic dispersion compensation, electronic predistortion (EPD), optical transmission.

I. INTRODUCTION

DIRECTLY modulated lasers (DMLs) as a low-cost device with a small form factor and low power consumption are very interesting for the use in 10-Gb/s metro networks. However, due to the laser chirp induced spectral broadening, the typical transmission limit in a transmission system with standard single-mode fibers (SSMFs) without dispersion compensation is about 20 km. A few techniques were proposed to expand this transmission limit without inline compensation of the chromatic dispersion. The dispersion supported transmission (DST) [1] uses a variable low pass filter at the receiver to invert the fiber transfer function. Here, transmission lengths up to 250-km SSMF have been reported. Another approach, the chirp managed laser, deals with an optical filter at the laser transmitter to generate a duobinary-like signal. As with the DST, the maximum transmission length with an SSMF is about 250 km [2].

In more expensive externally modulated transmission systems, the recently introduced electronic predistortion (EPD) technique is a completely different approach to overcome the dispersion limit [3], [4]. Due to the linearity of the dispersion in the optical domain, a predistorted optical signal at the transmitter, which compensates the effect of the chromatic dispersion, can be analytically calculated. Without optical dispersion compensation, transmission lengths of up to 3840 km are published [4]. Theoretically, it is possible to compensate any amount of distortions due to the chromatic dispersion, if a modulator is used that controls the real and the imaginary part of the calculated predistorted signal.

In this letter, the authors will introduce a new concept of EPD with a DML in a direct detection system. The main difference to a vector modulator is the dependence of the phase on the intensity at a DML. This means, a predistorted signal like for a vector modulator cannot be modulated by a DML.

However, in a direct detection system the phase information at the receiver is unimportant. Hence, the phase at the receiver will be used as a degree of freedom to deal with the phase dependency of the intensity at the laser. The purpose would be to obtain, for a given target format of the optical intensity at the receiver and a specified relation of the intensity and phase at the transmitter (i.e., the laser chirp), the predistorted injection current of the DML. In case of a small signal approximation, it is possible to calculate this predistorted optical intensity analytically. For a large signal predistortion, an artificial neural network will be used.

II. SMALL SIGNAL APPROACH

Before the artificial neural network will be introduced as a predistorter, the possibility to predistort the chromatic dispersion with a DML will be analyzed with a small signal approach. Consider the complex optical field amplitude

\[ E_{\text{in}}(t) = \sqrt{S_{\text{in}}(t)} \exp(j\phi(t) + j\omega t) \]  

with the mean optical emission frequency \( \omega_m \), the phase \( \phi(t) \), and the optical intensity \( S_{\text{in}}(t) \) as the fiber input, a fiber transfer matrix of the fiber can be derived [5]

\[ \left( \begin{array}{c} \Delta S_{\text{out}}(j\omega) \\ \phi_{\text{out}}(j\omega) \end{array} \right) = \left( \begin{array}{cc} \cos(\omega^2 F) & \frac{2j(S) \sin(\omega^2 F)}{\omega \cos(\omega^2 F)} \\ \frac{j \omega \sin(\omega^2 F)}{2(S)} & \cos(\omega^2 F) \end{array} \right) \cdot \left( \begin{array}{c} \Delta S_{\text{in}}(j\omega) \\ \phi_{\text{in}}(j\omega) \end{array} \right) \]  

with \( S_{\text{in/\text{out}}} = \Delta S_{\text{in/\text{out}}} + \langle S \rangle \) a small signal approximation of the optical intensity at the fiber input and output, respectively, \( \phi(j\omega) = \frac{d(\phi(j\omega))}{d\omega} \) the frequency modulation, \( \omega \) the angular frequency, and \( F \equiv \beta_2 L/2 \) a dispersion parameter with \( \beta_2 \) the chromatic dispersion and \( L \) the fiber length. Combining this transfer matrix (2) with the small signal behavior of a DML [6]

\[ \phi_{\text{in}}(j\omega) = \frac{\alpha}{2} (j\omega + \omega_g) \Delta S_{\text{in}}(j\omega) \]  

\[ \Delta S_{\text{in}}(j\omega) = \frac{\tau_{\text{ph}}}{e} H_{DL} \cdot \Delta I(j\omega) \]  

with \( \alpha \) the laser chirp and \( \omega_g \) the characteristic frequency of the laser, \( \tau_{\text{ph}} \) the photon lifetime, \( e \) the elementary charge, \( H_{DL} \) the small signal laser transfer function, and \( \Delta I \) the small signal laser injection current, a predistorted laser injection current can be calculated. The calculated predistorted current for a
nonreturn-to-zero (NRZ) modulation is used to modulate a rate equation based laser. The predistorted optical signal is then transmitted over a linear SSMF (nonlinearities are neglected). The dispersion parameter is $D = 16$ ps/km/nm. No optical and electrical filter are used at the receiver. Fig. 1 shows the extinction ratio of the predistorted signal after transmission. Even after 500 km, the received eye remains open, which shows in principle, that the EPD is possible with a DML. However, for practical applications, the extinction ratio is unrealistically small and a different large signal approach has to be used.

III. EPD WITH ARTIFICIAL NEURAL NETWORKS

The large signal EPD in this letter is based on an artificial neural network [7], which acts as a nonlinear signal processing unit (Fig. 2). In order to generate a predistorted signal with the neural net, the coefficients of the neural net will be estimated using the particle swarm optimization algorithm [8]. The particle swarm algorithm is a nondeterministic optimization algorithm, that finds the (global) minimum of a given fitness function in a multidimensional space. Fig. 3 shows the used optimization setup. As a training sequence, a De Bruijn bit sequence (DBBS) with $2^\alpha$ bit will be sent to the neural network. The output of the neural network modulates the DML (chirp factor $\alpha = 2$). The generated optical signal will be transmitted over a linear SSMF ($D = 16$ ps/km/nm), optically filtered using a second-order Gaussian bandpass (3-dB bandwidth of 20 GHz), detected by an ideal photodiode and electrically filtered by a low pass (3-dB cut-off frequency of 5 GHz, Bessel fifth order). Due to a lower computational effort of the optimization, the bit-error rate (BER) for the received signal will be calculated semi-analytically, applying a Gaussian approximation for the probability density function of the noise. The aim of the optimizer is to find the coefficients of the neural network, which results in the lowest BER for a given transmission distance. Having found the optimum coefficients for a selected transmission length, the required optical signal-to-noise ratio (OSNR) for a BER = $10^{-5}$ will be calculated using the more precise Monte Carlo method and a DBBS with $2^{10}$ bits. Gaussian white noise is added at the receiver and at least 40 errors are counted to obtain the OSNR. For comparison, also a DST system with the same laser and fiber parameters is examined.

IV. NUMERICAL RESULTS

As shown in Fig. 4 the typical characteristic of a DST system is the ascent of the required OSNR until a few ten kilometers (here 50 km). The same OSNR ascent occurs with the EPD signal, but leads to a significantly lower required OSNR at 50 km. Between 50 and 300 km, the required OSNR is less than 15 dB, between 150 and 250 km, even less than or equal to 12 dB. The maximum transmission distance with the EPD
signal is about 350 km with a required OSNR of about 16 dB. The dispersion tolerance with a penalty of 2 dB is about 70 to 100 km (Fig. 4). This is a remarkable result, as the dispersion tolerance for the conventional NRZ system is only about 10 km. The optical power spectrum (Fig. 5) may explain the good dispersion tolerance and the high system performance. With a growing predistortion distance, the optical power spectrum becomes narrower and thus, the impact of chromatic dispersion is reduced.

V. EXPERIMENTAL RESULTS

For the initial experiment of the EPD, no 10-Gb/s laser has been available in our laboratory. For this reason, the experiments at 10 Gb/s have been performed with a laser diode designed for 2.5 Gb/s (Agere D2555). The experimental setup is shown in Fig. 6. A personal computer (PC) controls the particle swarm optimization to obtain the neural net coefficients for the EPD. For this purpose, the EPD signal will be sent to the arbitrary waveform generator (Tektronix AWG7102) with a resolution of 20 GSamples/s and transmitted over the defined distance. The transmission link consists of two SSMF (each 95 km) with about 18-dB attenuation and a total dispersion of 3243 ps/km/nm. The fiber input power is 3 dBm. At the end of the link, the signal is optically filtered by a bandpass (50 GHz bandwidth) and detected with a p-i-n photodiode. A 20-GSamples/s oscilloscope (Tektronix TDS6804B) averages the received electrical signal in order to eliminate the influence of the noise. For performance reasons of the optimization, the BER as the fitness function of the particle swarm algorithm is estimated semi-analytically with the Gaussian approximation in the PC. The BER after EPD optimization is estimated with a digital oscilloscope and a sent De Bruijn sequence of 2^16 bit.

Fig. 7 shows the averaged eye diagram of the back-to-back signal and after 190-km transmission with EPD. Due to the use of a 2.5-Gb/s laser, both eyes are relatively poor. However, at 190 km, a remarkable open eye can be obtained using the introduced EPD technique. The received BER after 190 km is $8 \times 10^{-4}$ with 51 counted errors at 33.6-dB OSNR [9].

VI. CONCLUSION

A new approach for EPD with a DML based on a neural network was introduced. With that approach, a maximum transmission distance of 350-km SSMF was achieved by simulations with standard 10-Gb/s DML parameters. Experimentally, a transmission distance of 190-km SSMF was obtained using a commercially available 2.5-Gb/s DML.

REFERENCES