Improvement of the SPM Nonlinear Duobinary Limit by Chirped Duobinary Transmission (CDBT)

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Abstract: We investigate the performance of chirped duobinary transmission (CDBT) compared to conventional duobinary transmission. CDBT enlarges the dispersion limited transmission distance, increases the dispersion tolerance and overcomes the SPM nonlinear duobinary limit by the combined influence of pre-chirp, chromatic dispersion and SPM.

1. Introduction

It is well known, that the transmission performance of binary signals with negative pre-chirp in case of anomal dispersion ($D > 0$) is improved [1]. However positive pre-chirp reduces the transmission effectiveness. The self-phase modulation (SPM) effect increases the performance of pre-chirped binary transmission, for negative as well as for positive pre-chirped signals [2].

The benefits of duobinary transmission in the linear regime are well known. It enhances the bandwidth efficiency and dispersion tolerance, broadens the transmission distance and suppresses SBS [3-5]. However the improvement decreases rapidly in the nonlinear regime because of the SPM limit [6].

Up to now an optical duobinary signal is generated by a Mach-Zehnder modulator in push-pull configuration to ensure a chirp-free duobinary signal. Residual chirp of the Mach-Zehnder modulator reduces these benefits, because the chirp polarity of the signal alternates [7].

Chirped duobinary transmission (CDBT) is a method to generate a pre-chirped duobinary signal with fixed polarity (either positive or negative) [8]. We investigate the influence of pre-chirp on optical duobinary transmission and its performance related to optical input power level in comparison to conventional duobinary transmission (DBT). Furthermore we consider the dispersion tolerance of CDBT to show the relaxed dispersion compensation beyond the nonlinear duobinary limit.

2. Chirped duobinary transmission

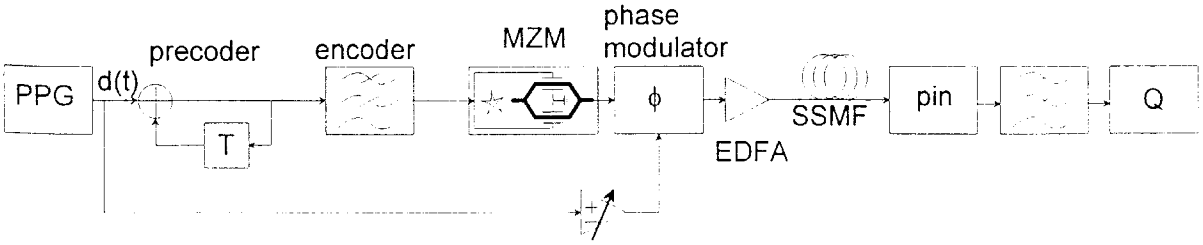


Fig. 1: system model of chirped duobinary transmission (CDBT)

The chirped duobinary transmitter consists of a conventional duobinary transmitter and an additional phase modulator. The binary NRZ signal *d(t)*, generated by a pulse pattern generator (PPG) with the data rate 10 Gb/s, is precoded and encoded to a ternary duobinary signal, that drives a Mach-Zehnder modulator in push-pull configuration to generate a chirp-free optical duobinary signal. The encoder is a Bessel lowpass filter (6th order, 2.7 GHz cut-off frequency). The pre-chirp is generated by a successive phase modulation proportional to the binary signal, resulting to the phase signal φ(t) ~ ΔΦ *d(t)*. The magnitude of the phase shift ΔΦ and the sign of the chirp is controlled by an amplifier at the input of the phase modulator.

The optical input power and the fiber length of standard single mode fiber (SSMF, D = 17 ps/nm/km, nonlinear coefficient $\gamma = 1.62\ (\mathrm{W\ km})^{-1}$) are varied. The receiver consists of pin diode and lowpass filter (Butterworth LPF, 2nd order, 7 GHz cut-off frequency).

3. Simulation results

We compare CDBT and DBT by calculating the Q-factor on the basis of an optical signal-to-noise ratio of 25 dB measured in 0.1 nm bandwidth. We simulate various fiber lengths and optical input power levels and choose the optimum phase shift ΔΦ for maximum Q-factor. The results are shown in fig. 2(a). Considering the Q-factor along the fiber, CDBT outperforms DBT. There is only a small improvement in the linear regime but it significantly improves in the nonlinear regime. The maximum fiber length that fulfills the transmission quality criterion Q > 10 is defined as transmission distance. The transmission distance of CDBT increases significantly to 130% of the DBT distance at 15 dBm optical input power.

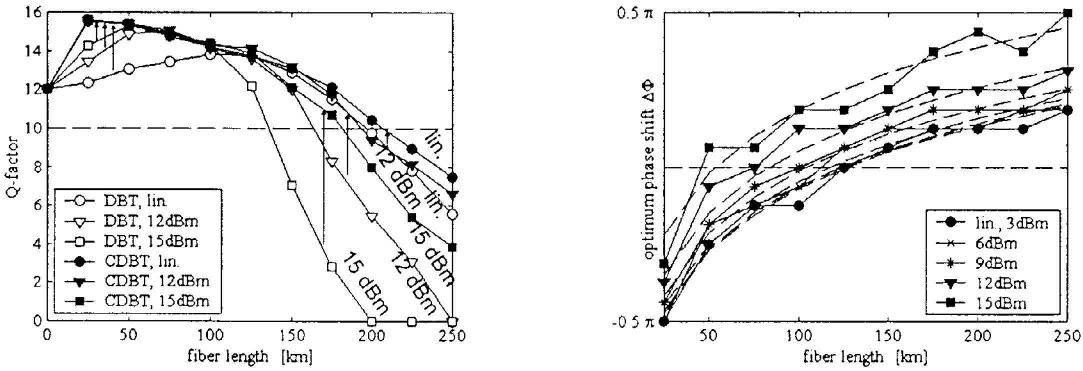


Fig. 2. Q-factor related to fiber length for optimized CDBT and chirp-free DBT transmission in the linear and nonlinear regime (12 dBm, 15 dBm) (a) and optimized phase ΔΦ of CDBT and its logarithmic approximation (b)

The optimum phase shift related to fiber length and optical input power is shown in fig. 2(b). Considering short fiber length in the linear regime negative pre-chirp improves the Q-factor. For long distance the optimum pre-chirp becomes positive. With increasing optical input power the optimum phase shift increases.

We approximate the characteristics of the curves by a logarithmic function depending on the fiber length L (in km) and vertically shifted by the value of optical input power P (in mW)

$$\Delta\Phi = \Phi_0 \left(\lg\left(\frac{L}{L_0}\right) + \frac{P}{P_0} \right). \tag{1}$$

Optimizing the curve fitting the parameters are Φ_0=2.1 rad, P_0=80.7 mW and L_0 = 130.7 km.

In a second set of simulations we have considered a dispersion compensated single span system. The fiber length of the SSMF is 100 km followed by dispersion compensating fiber (DCF) in the linear regime. We have calculated the dispersion tolerance, that is the range of dispersion compensation resulting in Q>10. The result for DBT reported in [6] shows a substantial drop of dispersion tolerance for optical powers > 8dBm, that is called nonlinear duobinary limit (fig. 3 (a)). CDBT shifts this nonlinear duobinary limit by 3 dB to enable more relaxed dispersion compensation at high optical powers. The optimum phase shift of

CDBT in the dispersion compensated system increases with increasing optical input power and is shown in fig. 3(b).

4. Discussion

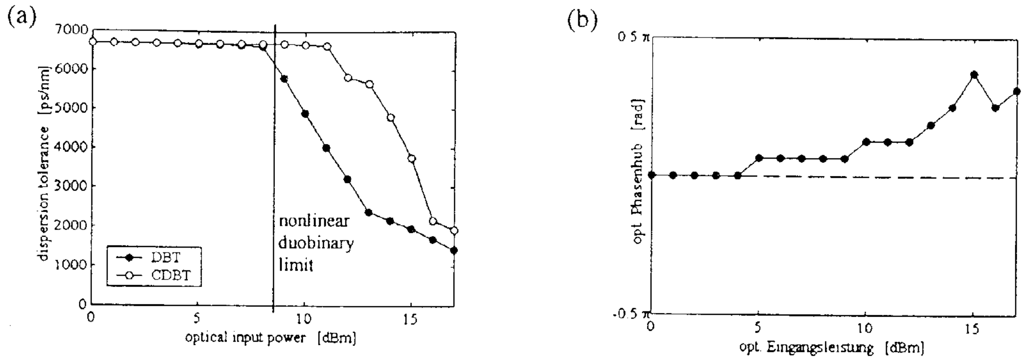
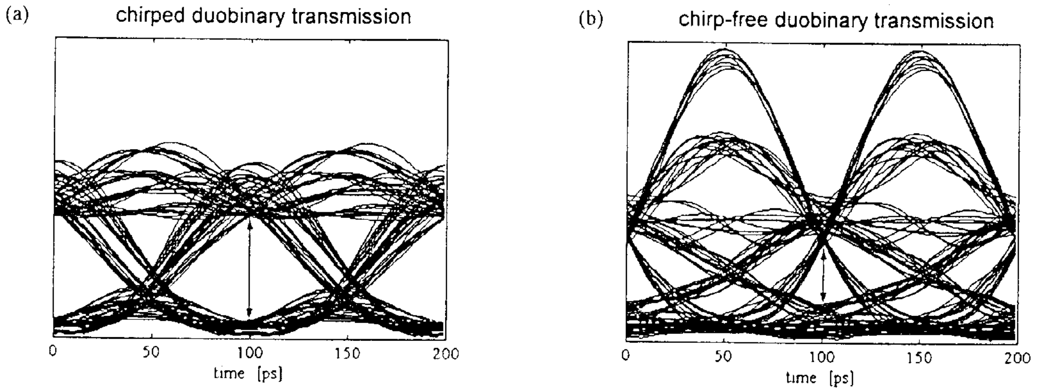


Fig. 3. Dispersion tolerance of DBT and CDBT after 100 km SSMF related to optical input power (a) and optimized phase shift ΔΦ of CDBT (b)

It is well known, that duobinary encoded signals are less sensitive to chromatic dispersion due to the bandwidth reduction by approximately a factor of two compared to binary transmission. However the dispersion tolerance of DBT in the nonlinear regime decreases significantly compared to the linear regime. For high optical powers the bandwidth of optical duobinary signals is distinctly enlarged by the SPM effect [6]. The combined influence of strong SPM effect and chromatic dispersion deforms the chirp-free DBT signal severely [6, 9]. This is shown by the eye diagram in fig. 4 (b) after 175 km SSMF and for 15 dBm optical input power. The eye diagram of optimized CDBT is clearly open as is shown in fig. 4 (a). The optimum value of the (positive) pre-chirp counteracts the signal distorting influence of SPM. This effect can be shown in the spectral domain.


(a) chirped duobinary transmission

(b) chirp-free duobinary transmission

Fig. 4. Eye diagram of chirped duobinary transmission (a) and chirp-free duobinary transmission (b) after 175 km standard single mode fiber in the nonlinear regime (15 dBm)

The improved dispersion tolerance of CDBT in the nonlinear regime is due to the narrower spectrum of the optical signal compared to DBT. We have simulated the power density spectrum of the optical field after 150 km fiber length. The results are shown in fig. 5 for a 95 %-bandwidth (bandwidth that contains 95 % of the total signal power, normalized to the bandwidth of DBT in the linear regime) versus optical input power. For high optical powers the bandwidth of DBT is dominated by the SPM induced spectral broadening resulting in raising dispersion sensitivity. CDBT with optimized phase shift, calculated by equation (1), results in a reduction of the spectral bandwidth arising less distortion of the signal and increased transmission effectiveness in the time domain.

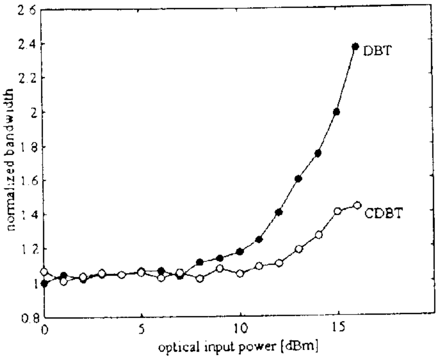


Fig. 5: Normalized bandwidth of optical field depending on input power after 150 km DBT and CDBT

5. Conclusion

We have compared the dispersion tolerance of chirped duobinary transmission (CDBT) related to conventional duobinary transmission. CDBT increases the performance significantly and broadens the transmission distance especially in the nonlinear regime. The optimum phase shift related to fiber length and optical input power is approximated by a logarithmic equation. CDBT overcomes the nonlinear duobinary limit to enable a relaxed dispersion compensation beyond the nonlinear duobinary limit. An explanation of the improvement has been given by a bandwidth model.

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