Differentielle vierstufige Phasenumtastung zur kostengünstigen Verdopplung der Kapazität in bestehenden WDM-Systemen

Differential quadrature phase-shift keying for cost-effective doubling of the capacity in existing WDM systems

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Kurzzusammenfassung

Die Steigerung der spektralen Effizienz stellt eine Möglichkeit zur kostengünstigen Erhöhung der Kapazität in bestehenden WDM Systemen dar. In diesem Beitrag soll die differentielle vierstufige Phasenumtastung (DQPSK) vorgestellt werden, mit der es möglich ist, die Kapazität in einem bestehenden System zu verdoppeln, ohne dabei teures hochbitratiges Equipment einsetzen und das bestehende 10Gb/s Systemmanagement anpassen zu müssen. Damit ist DQPSK ein sehr kostengünstiges Verfahren. Es wird auf den Zusatzaufwand beim Aufbau von Sender und Empfänger eingegangen. Außerdem wird mit Hilfe von Messergebnissen gezeigt, dass DQPSK bei einer Datenrate von 20Gb/s (=Symbolrate 10GSymb/s) eine zur herkömmlichen Intensitätsmodulation (ASK) bei 10Gb/s Datenrate vergleichbare Empfängerempfindlichkeit und Dispersionstoleranz aufweist. Schließlich werden Simulationsergebnisse vorgestellt, die eine höhere Toleranz von DQPSK gegenüber nichtlinearen Effekten belegen, obwohl die Datenrate im Vergleich zu ASK doppelt so hoch ist.

Abstract

Improving the spectral efficiency is one possibility to increase the capacity of existing WDM systems. In this paper, we introduce differential quadrature phase shift keying (DQPSK) which allows to double the capacity of existing systems by neither using expensive high bit rate equipment nor changing the existing 10Gb/s system management. This is why DQPSK can be considered as cost effective. The additional effort to implement the transmitter and receiver is discussed. Moreover, by means of measurement results it is shown that DQPSK at a data rate of 20Gb/s (=symbol rate 10GSymb/s) exhibits a similar receiver sensitivity and dispersion tolerance compared to conventional on/off keying (ASK). Finally, simulation results confirm a higher tolerance of DQPSK towards nonlinear effects although the data rate is doubled compared to ASK.

1 Introduction

Increasing the spectral efficiency of an optical data transmission system is considered very cost effective for enlarging the transmission capacity. In this paper, we demonstrate a spectral efficiency of 0.8b/s/Hz by using the differential quadrature phase-shift keying (DQPSK) modulation format for fiber optic transmission. DQPSK is a well known technique in classical communications and has recently also been considered for optical communications because it doubles the spectral efficiency and shows an excellent robustness to signal degradation [1,2]. This approach is very promising, because i.e. the resulting, single wavelength bit rate of 20Gb/s can be transmitted at a symbol rate of 10GSymbol/s. This implies that this transmission format is as tolerant as standard amplitude-shift keying (ASK) transmission with just half the data rate to impairments like PMD, dispersion tolerance and nonlinear effects.

The paper is organized as follows: First, the transmission setup for DQPSK with return-to-zero pulse shape is explained that allows an easy setup to double the capacity. Second, the receiver sensitivity and dispersion tolerance of DQPSK is investigated by measurements and simulations and compared to ASK.

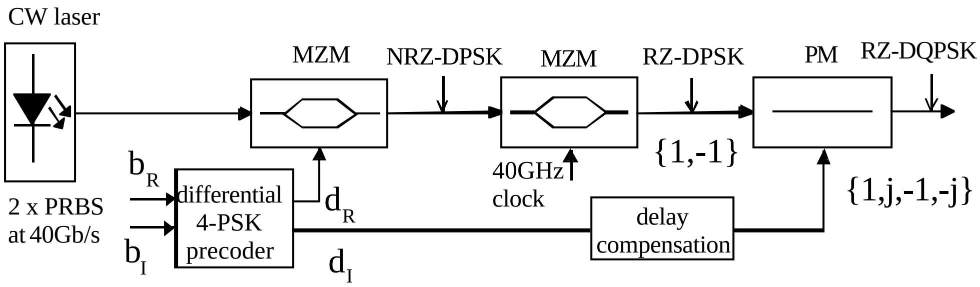

Fig. 1 How to generate an RZ-DQPSK signal

Finally, the performance of RZ-DQPSK and RZ-ASK are investigated in a high bit rate WDM setup. The simulation results reveal a high tolerance of DQPSK towards nonlinear fiber effects.

2 Proposal for RZ-DQPSK transmission setup

In most DQPSK systems in classical digital communications the four-symbol signal is generated by superposing two bipolar modulated carriers that exhibit the same frequency but have a 90° phase shift to each other [3]. It is difficult to adapt this concept to optical communications because the required phase shift of 90° has to be guaranteed until the signals are merged by a 3dB coupler. In a recent optical DQPSK proposal [1] this problem is overcome by O/E converting part of the transmitter signal and feeding it to a servo-control loop. We avoid this problem by a DQPSK transmitter setup shown in fig. 1.

The first two Mach-Zehnder modulators (MZM) form a chirp-free binary DPSK signal with RZ pulse shape (CF-RZ-DPSK [4]). The subsequent phase modulator (PM) with a phase shift of either 90° (d_I=1) or 0° (d_I=0) generates four symbols out of the binary PSK signal, see fig. 2a). This concept requires only electrical tuning of the PM input data within a bit duration by a delay compensation. Fig. 2) shows that the signal has almost no power during bit transitions and is thus inherently chirp free. This is advantageous considering the effect of group velocity dispersion (GVD).

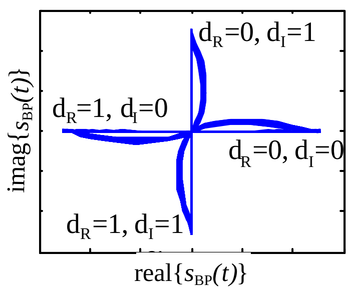

Fig. 2 Trajectories of RZ-DQPSK signal constellation in complex plane

Fig. 1 also shows that for transmitting RZ-DQPSK with a bit rate of 20Gb/s or 80Gb/s, respectively, the electronic components only have to operate at the symbol rate of 10GSymb/s or 40GSymb/s, respectively.

The differential QPSK precoder [3] is necessary in order to use the simple receiver [1] in fig. 3 with an optical filter (delay line T_S= symbol duration) and two balanced receivers.

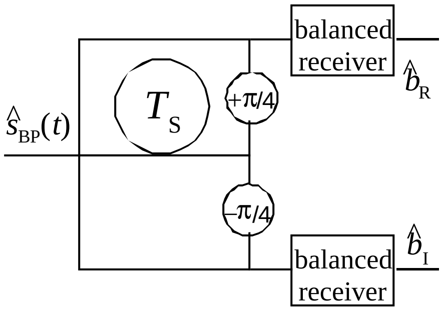

Fig. 3 DQPSK direct detection receiver

3 Investigation of receiver sensitivity

The receiver sensitivity is one of the most important properties of a modulation format. In this section, the setup for measuring the receiver sensitivity of DQPSK is described (fig. 4) and the results are compared with conventional ASK format.

The transmitter consisted of an external cavity laser (ECL) operating at a wavelength of 1539.75nm followed by two $LiNbO_3$ Mach-Zehnder modulators (MZM) that were operated in push-pull mode. The first MZM was driven with the 10GHz clock signal to generate the RZ-pulse train. This was done by biasing the modulator at the zero in its power-voltage characteristic. The second MZM was used to form a phase-shift keyed signal. This MZM was biased at the zero in its characteristic curve, too. It was driven with a 10Gb/s non-return-to-zero (NRZ) electrical pseudo random bit sequence (PRBS) of length 2^9-1. This sequence is referred to as d_R because it forms the real part of the RZ-DQPSK signal. The phase modulator (PM) consisted of a single $LiNbO_3$ optical wave guide

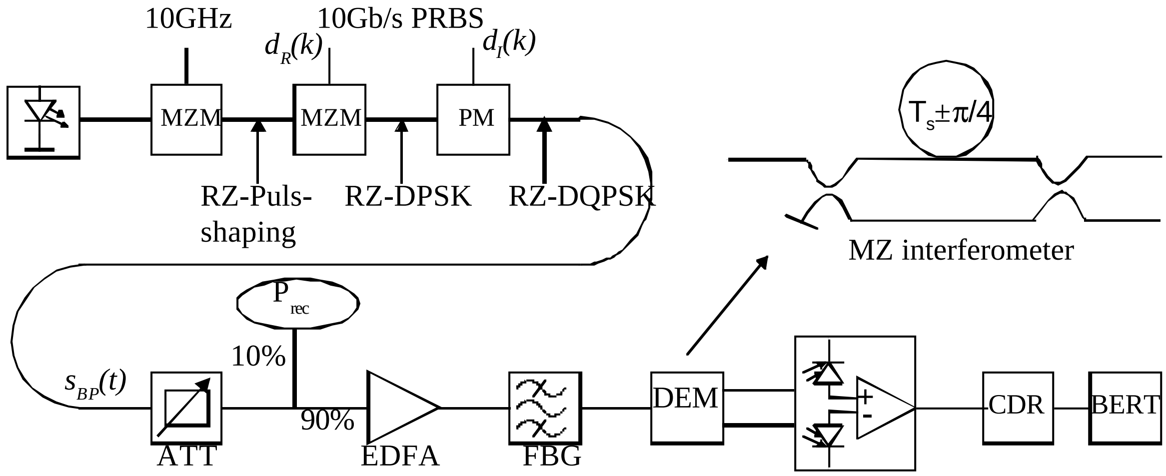

Fig. 4 Experimental setup for RZ -DQPSK at 20Gb/s with autocorrelation detector

with one electrode. It was driven with the complementary PRBS signal as used for the second MZM. According to the PRBS signal d_R, this sequence is referred to as d_I because it forms the imaginary part of the RZ-DQPSK signal. The driving voltage of the PRBS signal was adjusted to achieve a phase shift of 90° for the high level representing the "1" at the electrical input and 0° for the low level representing the "0". An RF phase shifter was used to align the bit slots of both data streams d_R and d_I. It should be noted that the transit time for the optical signal from the second MZM to the PM was 10.5ns. This delay is sufficient to ensure that the two PRBS signals are uncorrelated.

An optical monitor coupler was used to measure the power of the transmitted signal before entering the 2-stage preamplifier. The small-signal gain and the noise figure of the erbium-doped fiber amplifier (EDFA) were 32dB and 4.5dB, respectively. Two external optical isolators (insertion loss: 0.2dB each) were placed in front of the preamplifier. After amplifying the signal it was filtered by a fiber bragg grating (FBG) with a center frequency of 1539.75nm and a bandwidth of 0.2nm to suppress the out-of-band ASE noise.

The real (in-phase) and imaginary (quadrature) part of the DQPSK signal were detected by a Mach-Zehnder interferometer (MZI) that incorporated a delay of one symbol duration of 100ps (autocorrelation detector). It was based on two spliced fiber couplers. The phase difference between the signal and its delayed replica was adjusted thoroughly via temperature control of the length of the arms of the MZI. To detect the real and imaginary component of the DQPSK signal the phase difference of the two band-pass signals has to be adjusted to +45° and –45°, respectively. In this way both components were measured separately on a data rate of 10Gb/s per tributary. It is worth noting that this MZI is the same that is used for detecting binary DPSK signals. The two outputs from the MZI were fed to a commercially available, low-noise balanced receiver with a bandwidth of 14GHz. The optical path lengths to the balanced receiver were roughly guaranteed by an appropriate splicing. In case of single-ended detection only one output of the MZI was used and connected to a standard photo diode with 12GHz bandwidth. After clock- and data recovery (CDR) the BER was measured.

For these measurements there was no differential quaternary precoder available. In contrast to binary DPSK transmission the precoded PRBS signal is not simply the delayed PRBS input signal. This problem was bypassed by taking into account that the input data streams are mapped to the output of the transmission line in a deterministic way. Thus, BER-measurements were allowed by programming the BER-tester with the expected data sequences at the receiver. To determine the expected data streams at the receiver the transit time from the second MZM to the PM has to be considered.

We use binary NRZ-ASK as a reference and a basis for comparison with our DQPSK format. To measure the performance of binary NRZ-ASK format a similar setup as in fig. 4 was used. For generating the NRZ-ASK signal the MZM for RZ pulse carving and the phase modulator was omitted. Moreover, the receiver-MZI was left out, too. Note that the transmission bit rate for DQPSK is 20Gb/s whereas for ASK it is 10Gb/s only.

The measured eye diagram for the imaginary channel of RZ-DQPSK with balanced detection is given in fig. 5. To measure these eye diagrams the received power at the preamplifier was set to –10dBm to reduce the noise sufficiently.

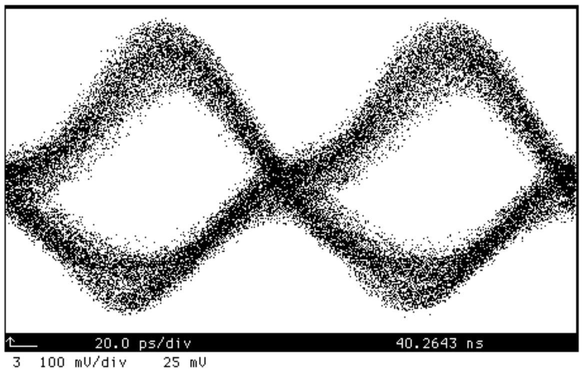

Fig. 5 Measured eye diagrams for imaginary channel of RZ-DQPSK at 20Gb/s

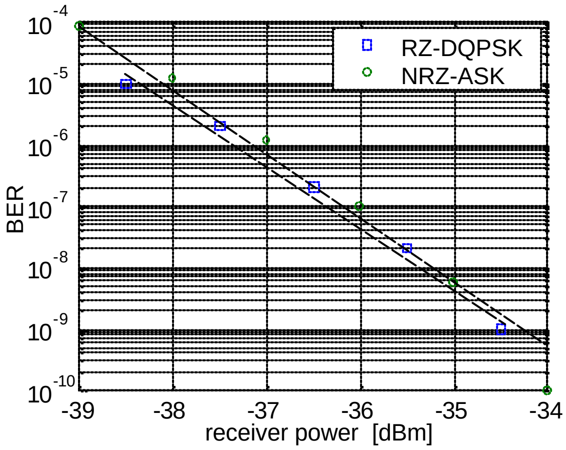

Fig. 6 Measured BER values for NRZ-ASK format at 10Gb/s and RZ-DQPSK at 20Gb/s, respectively

To understand the results depicted in fig. 6 three effects that influence the receiver sensitivity have to be considered: first, the minimum symbol distance of ASK and DQPSK, second, the improvement of RZ pulse-shaping over NRZ, and third, the penalty due to direct detection of DQPSK.

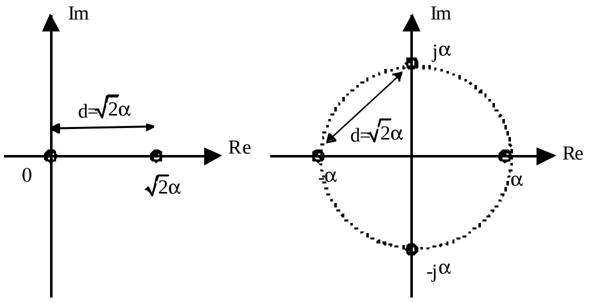

Fig. 7 ASK (left) and DQPSK (right) in complex plane, for same average power, pulse shape and symbol rate

First, the minimum distance between the transmitted symbols in the complex plane determines the error performance of a signaling technique if optimum (coherent) detection is considered. For the same average power, the same pulse shape and the same symbol rate ASK and DQPSK are depicted in the complex plane (fig. 7).

One can see that the minimum distance of the symbols is the same for both formats even if DQSK allows to transmit twice as much data compared to ASK.

Second, if the receiver sensitivity of RZ and NRZ modulation formats are compared (in case of conventional optical and electrical receiver filters) RZ formats outperform NRZ techniques by approximately 2dB [5]. These facts contribute to an advantage of RZ-DQPSK over conventional NRZ-ASK of 2dB.

Third, it must also be considered that a MZ interferometer is used as a differential receiver. This is an autocorrelated reception [7] where a delayed replica of the received signal is used to enable detection without a local oscillator (LO). In [6] it is shown, that this induces an additional power penalty for DQPSK with direct detection compared to coherent detection, which incorporates an LO with phase and frequency synchronization. For DQPSK transmission a penalty of at least 2dB is obtained compared to ASK as shown theoretically in [7].

To summarize the considerations above, on the basis of equal symbol distance DQPSK and ASK have equal receiver sensitivity. RZ-pulse shaping gives RZ-DQPSK an advantage of approximately 2dB over NRZ-ASK. At the same time the introduction of DQPSK (that doubles the bit rate) in conjunction with direct detection introduces a power penalty of at least 2dB compared to binary ASK. For the measurement setup shown in fig. 4, the effects that improve and these that degrade the receiver sensitivity of 20Gb/s-RZ-DQPSK compared to 10Gb/s-NRZ-ASK cancel each other. This leads to the same receiver sensitivity (see fig. 6), the same OSNR requirements and the same occupied bandwidth of the considered formats even if DQPSK allows to transmit twice as much data.

4 Investigation of dispersion tolerance

As stated in the introduction, the DQPSK format allows to transmit twice as much data within the same spectral width (that is determined by the symbol duration) compared to a binary technique. It is a well known fact, that the width of a data spectrum is a good indicator for the dispersion tolerance of the corresponding signal. Thus, it can be concluded that the dispersion tolerance of a DQPSK format is the same as a binary technique with just half the data rate. This conclusion however holds only for signals having the same pulse shape. Therefore in the following the dispersion tolerance of RZ-ASK and RZ-DQPSK is compared. In figure 8, the data spectrum of RZ-ASK at data rate of 10Gb/s and RZ-DQPSK at a data rate of 20Gb/s are depicted.

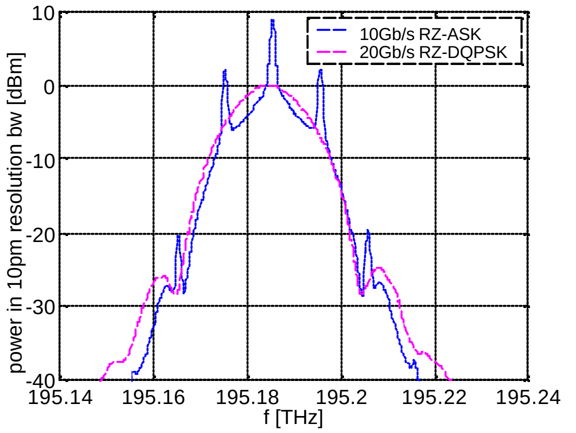

Fig. 8 Measured data spectrum of RZ-ASK at 10Gb/s and RZ-DQPSK at 20Gb/s

For illustration, the table below quantifies the spectral width of both formats for which the power spectrum has dropped by 20, 30, and 40dB compared to the value at the carrier frequency.

decay ΔP [dB]	RZ-ASK 10Gb/s Δf [GHz]	RZ-DQPSK 20Gb/s Δf [GHz]
-20	36.2	36.2
-30	55.0	56.5
-40	72.5	77.5

Tab. 1 Two sided spectral width of RZ-ASK and RZ-DQPSK

The spectral width, that defines the decay of the spectrum by 20dB, is -36.2GHz for both RZ-DQPSK and RZ-ASK. Note, that the data rate is 20Gb/s for RZ-DQPSK and only 10Gb/s for RZ-ASK. This confirms the fact, that the spectral efficiency can by doubled by DQPSK in comparison to binary transmission formats that exhibit the same pulse shape. It is worth noting that the width for decays of the spectrum larger than 20dB is slightly higher for RZ-DQPSK in comparison to RZ-ASK.

Finally, the dispersion tolerance is investigated for RZ-DQPSK at 20Gb/s and RZ-ASK at 10Gb/s by measuring the eye opening penalty (EOP) for a residual dispersion between +/-1275ps/nm (1275ps/nm corresponds to an uncompensated link of 75km SSMF). Fig. 9 confirms the considerations that were derived from the spectral properties: RZ-DQPSK at a data rate of 20Gb/s shows nearly identical dispersion tolerance compared to RZ-ASK at 10Gb/s.

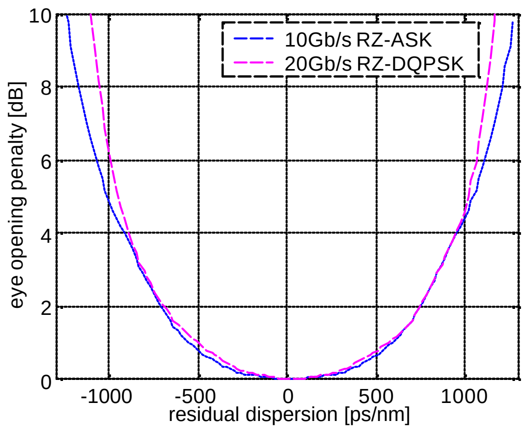

Fig. 9 Simulated dispersion tolerance of RZ-ASK at 10Gb/s and RZ-DQPSK at 20Gb/s in the linear regime of the fiber

Only for values of residual dispersion higher than 800ps/nm the EOP induced by dispersion is higher for RZ-DQPSK. This might be explained by the fact that the width for decays of the spectrum larger than 20dB is slightly higher for RZ-DQPSK in comparison to RZ-ASK (see tab.1).

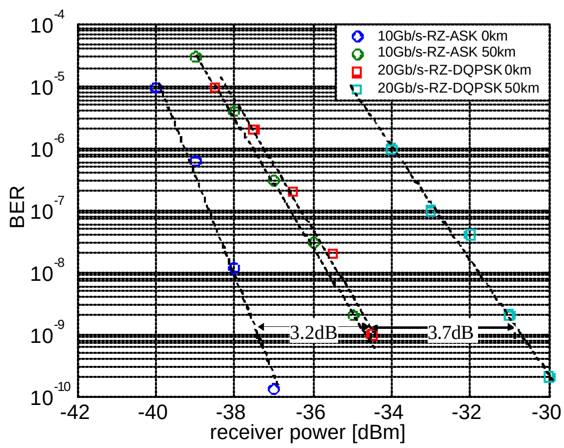

Fig. 10 Measured BER values versus receiver power for 10Gb/s-RZ-ASK and 20Gb/s RZ-DQPSK after 0 and 50km of SSMF

The simulation results in fig. 9 were also confirmed by measurement results that are depicted in fig. 10. Both formats were transmitted over 0km and over 50km of uncompensated SSMF using a similar setup to that shown in fig. 4. The BER and the corresponding signal power at the receiver was measured.

For a fixed BER of 10^{-9}, one can read a similar receiver penalty of 3.2dB and 3.7dB for RZ-ASK and RZ-DQPSK, respectively for the 50km SSMF-transmission.

5 Robustness to nonlinear effects in WDM systems

Besides receiver sensitivity and dispersion tolerance, the robustness of a modulation format towards nonlinear effects is important. This ensures that the WDM signal can propagate in the optical domain over a long distance without regeneration. To demonstrate that RZ-DQPSK shows a higher tolerance to nonlinear effects in comparison to RZ-ASK, both formats are investigated in the WDM setup of fig. 11.

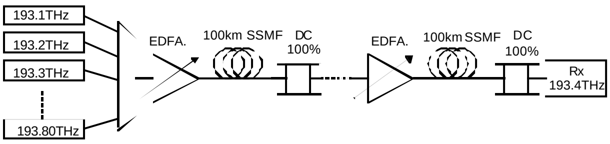

Fig. 11 WDM setup

The DWDM signal consists of 8 multiplexed channels in either RZ-DQPSK or RZ-ASK modulation format with a data rate of 80Gb/s and 40Gb/s per channel, respectively (channel spacing 100GHz, conform to ITU-T G.692). The optical multiplexer is modeled as an Arrayed-Waveguide Grating with a Gaussian shaped transfer function for each channel (B_{3dB}=72GHz). The RZ-DQPSK transmission setup is described in the previous section. The conventional RZ-ASK transmitter consists of two MZM. For RZ-DQPSK and RZ-ASK the 8-channel DWDM signal (PRBS length 2^{10}-1) passes through 4 fiber spans. Each span consists of 100km of a standard single mode fiber followed by a dispersion compensating fiber and a noiseless optical amplifier. The average fiber input power per channel in each span is varied between 0 and 9dBm. The length of the DCF is chosen such that the 4^{th} channel (f_T=193.4THz) is fully compensated. At the receiver side a channel selection filter with a bandwidth of 100GHz filters the signal at a center frequency of 193.4THz. The DQPSK receiver of fig. 3 is used with two balanced receivers and an electrical lowpass filter (Butterworth, 3rd order, f_{3dB}=28GHz).

In fig. 12 and 13, we show the simulation results. To understand the influence of the various nonlinear effects separately, two types of WDM simulation methods are carried out. The first considers linear crosstalk and full Kerr nonlinearity (SPM, XPM and FWM). For the second, we neglected XPM and FWM in our simulation [4]. In fig. 12, we measure the eye opening penalty (EOP) of the 4^{th} channel for both WDM systems respectively normalized to the back-to-back case as a function of the average fiber input power per channel P_{in}.

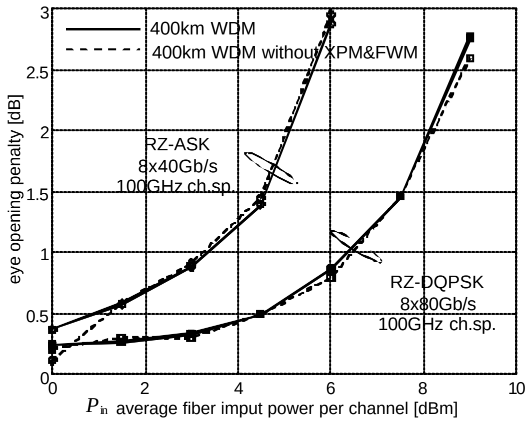

Fig. 12 Eye opening penalty over P_{in} for 8x40Gb/s-RZ-ASK, 8x80-Gb/s-RZ-DQPSK: WDM (lin. Xtalk, SPM, XPM, FWM), WDM without XPM&FWM

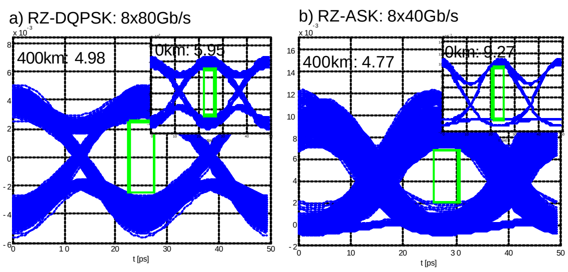

Fig. 13 Eye opening of a): 80Gb/s-RZ-DQPSK and b): 40Gb/s-RZ-ASK, P_{in}=6dBm, 400km, 100GHz ch.sp., WDM considering lin. Xtalk, SPM, XPM, FWM

The eye diagrams of the 40Gb/s-RZ-ASK signal and the 80Gb/s-RZ-DQPSK signal at 193.4THz and for 6dBm average fiber input power in case of full Kerr nonlinearities are shown in fig. 13 in comparison to the back-to-back eye diagrams.

Our simulation results (fig. 12 and 13) indicate that RZ-DQPSK with a spectral efficiency of 0.8b/s/Hz tolerates even higher input powers than RZ-ASK with just 0.4b/s/Hz spectral efficiency.

Fig. 12 shows that in the case of the considered WDM-system for an EOP of 1dB RZ-DQPSK tolerates approx. 3dB more input power compared to RZ-ASK.

This indicates that the advantageous properties of binary DPSK that are shown in e.g. [8,4] can be transferred to (quadrature) RZ-DQPSK. By comparing the simulation methods with (i) full Kerr nonlinearity (solid line) and (ii) neglecting XPM and FWM (dashed line) in fig. 12, it can be noticed that for RZ-ASK and RZ-DQPSK the most important impairment is SPM in agreement with [9]. Nearly no additional degradation through XPM and FWM can be seen.

6 Conclusion

We propose DQPSK transmission in fiber optic WDM systems. We demonstrated that RZ-DQPSK can show a similar receiver sensitivity and dispersion tolerance compared to conventional ASK formats even if the data rate is doubled compared to ASK. This allows an easy and cost-effective upgrade of existing WDM systems to double the capacity. Simulation results of an WDM system with high spectral efficiency demonstrated that RZ-DQPSK shows also an higher robustness towards nonlinear fiber effects compared to RZ-ASK.

7 Acknowledgment

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8 References

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