CF-RZ-DPSK: A new modulation format to suppress XPM on long-haul DWDM systems over SSMF

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Abstract

We present a new optical modulation format CF-RZ-DPSK that enables DWDM transmission at 10Gb/s/ch over 3000km without significant impairments due to XPM. The robustness towards XPM is shown by simulations and in an experimental setup by BER-measurements.

1 Introduction

Cross-phase modulation (XPM) is one of the most important nonlinear impairments that limit the performance of today's long-haul DWDM systems [1,2]. One way to overcome this limit is to find modulation formats that show a high robustness towards XPM. We introduce such a modulation format that we call chirp-free return-to-zero differential phase shift keying (CF-RZ-DPSK).

The paper is organized as follows: First, the transmission setup for CF-RZ-DPSK is explained. Second, to motivate CF-RZ-DPSK for long-haul transmission, we present simulation results of an 8-channel DWDM fiber link over 3000km of standard single mode fiber (SSMF) at a data rate of 10 Gb/s/ch with a channel spacing of 100GHz and high input peak power of 9dBm/ch.

Finally, to confirm the simulation results, we present experimental BER-measurements of a 2x10Gb/s DWDM system. Both, the simulation and the experimental results indicate that the impact of XPM is negligible for the CF-RZ-DPSK format whereas for conventional intensity modulation with RZ pulse shape (RZ-ASK) cross-phase modulation causes strong performance degradation.

2 Proposal for CF-RZ-DPSK transmission setup

In the following, we present our CF-RZ-DPSK transmission setup. We use differential PSK because no carrier recovery and synchronization is needed. Easy reception with direct detection equipment is possible if an optical delay-and-add filter is inserted in front of the photodiode [3]. Nevertheless, to receive the original data it is necessary to use a differential precoder [4].

The precoded data is modulated onto the optical carrier using a Mach-Zehnder modulator (MZM) in push-pull-operation (**fig. 1**). The MZM is driven in a way that the '1'-bit corresponds to the carrier phase shift of 0 and the '0'-bit corresponds to carrier phase shift of π. Both states have the same optical power. Therefore, after the first MZM an optical NRZ-DPSK signal is generated which is in contrast to [3,5] inherently chirp free, but has an optical power that goes down to zero during a symbol transition if two consecutive symbols are unequal.

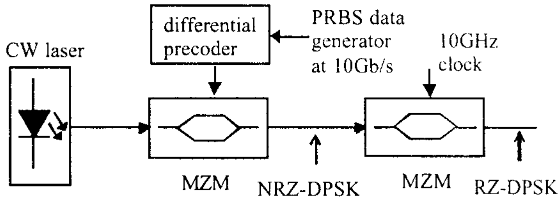

Fig. 1 How to generate a CF-RZ-DPSK signal

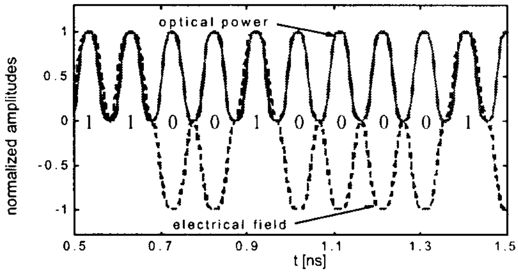

Fig. 2 Non-periodic electrical field and periodic optical power of CF-RZ-DPSK signal

The subsequent MZM is used to create an RZ pulse shape. This is done by driving it with the 10GHz clock signal. In contrast to NRZ-DPSK, where the optical power goes down to zero only during symbol transitions if two consecutive symbols are unequal, for RZ-DPSK the optical power goes down to zero for *any* symbol transition. Therefore, the optical power as a function of time is not pattern-dependent any more but is a deterministic and periodic signal. Thus, the unique property of CF-RZ-DPSK arises from the fact that the optical power of each channel has only frequency components at ± 10GHz (see **fig. 2**).

In [8], we show theoretically that because of this property the impact of XPM on CF-RZ-DPSK is reduced significantly. This is done by introducing a linear lowpass model: The XPM-induced phase modulation $\phi_{1,\mathrm{XPM}}(t)$ of the disturbed channel can be modeled as the output signal of a linear system $H_{12}(f)$, where the optical power of the disturbing channel $P_2(t)$ is the input signal. This linear system turns out to be of lowpass character. The cutoff frequency can be derived as $f_c=\alpha/2\pi D\Delta\lambda$, where α, D and $\Delta\lambda$ account for fiber loss, fiber dispersion and channel spacing, respectively. f_c is significantly below the data rate (e.g. f_c =540MHz for a loss of 0.2dB/km, D=17ps/(nm·km) and a channel spacing of 100GHz).

For CF-RZ-DPSK, the discrete components of the optical power at ± 10GHz are strongly attenuated by $H_{12}(f)$. This yields significantly less XPM-induced crosstalk compared to RZ-ASK (see. **fig 3**).

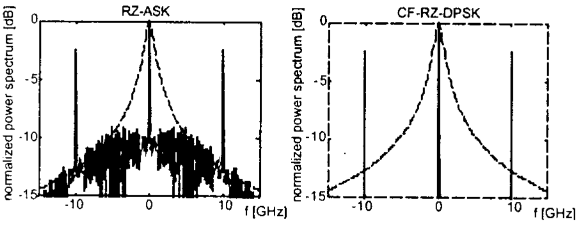

Fig. 3 Simulated spectrum of the optical power of the disturbing channel for RZ-ASK (left) and CF-RZ-DPSK (right). The dashed lines characterize the absolute value of $H_{12}(f)$ with f_c =540MHz.

3 Motivation for CF-RZ-DPSK in long-haul DWDM system

To motivate CF-RZ-DPSK for WDM long-haul transmission, we compare it by simulation with RZ-ASK.

The line rate and channel spacing of the WDM system are 10Gb/s and 100GHz, respectively. The DWDM signal consists of 8 multiplexed channels in CF-RZ-DPSK or RZ-ASK modulation format with a peak power of 9dBm per channel. The 8-channel DWDM signal passes through 30 fiber spans. Each span consists of 100km of standard single mode fiber followed by a dispersion compensating fiber and an optical amplifier. The length of the DCF is chosen such that the 4h channel (f_T=193.4THz) is fully compensated. After the last span an additional dispersion element is provided which is designed to optimize the residual dispersion in order to obtain an optimal eye opening. The receiver consists of a channel selection filter with a bandwidth of 100GHz that filters the signal at a center frequency of 193.4THz, a photodiode and an electrical lowpass filter (Butterworth, 2nd order, $f_{3\mathrm{dB}}$=10GHz).

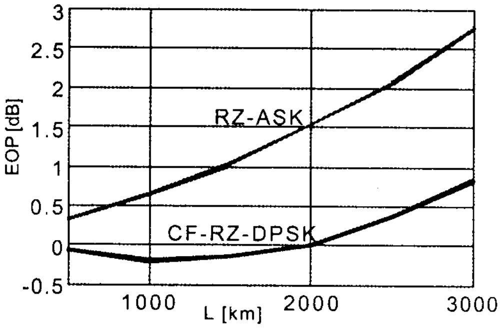

Fig. 4 8x10Gb/s with Δf=100GHz, peak power P_{in}=9dBm/ch: full Kerr-nonlinearity: SPM, XPM, FWM: eye opening penalty of 4th channel with increasing transmission length for CF-RZ-DPSK and RZ-ASK

We measure by simulation the eye opening penalty (EOP) for both RZ-ASK and CF-RZ-DPSK transmission as a function of transmission length. For an input peak power of 9dBm per channel, the simulation considers full Kerr-nonlinearity (SPM, XPM, FWM). By transmitting 10Gb/s with a channel spacing of 100GHz, because of phase mismatching [9] FWM causes only small signal distortions even for the high input power used whereas the effect of SPM is reduced significantly by dispersion management. Thus, the signal degradation is primarily caused by XPM.

The results in **fig. 4** show the superior performance of CF-RZ-DPSK. Even for 3000km the penalty for CF-RZ-DPSK remains under the 1dB threshold. In [8], we show that XPM turns out to be the limiting effect for RZ-ASK.

4 Experiments

To confirm the above simulation results, we would need a loop experiment that was not available.

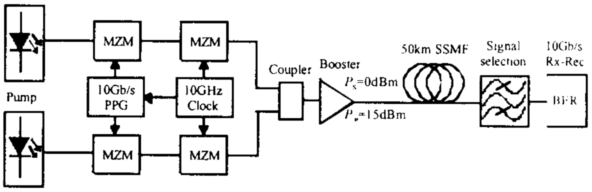

Fig. 5 Experimental setup: 2x10Gb/s, P_s=0dBm and P_p=15dBm, channel spacing 0.32nm over 50km SSMF

Nevertheless, it is possible to compare the performance of CF-RZ-DPSK and RZ-ASK in presence of XPM in an experimental 2x 10Gb/s DWDM setup. The setup (**fig.5**) is suited to generate a strong impact of XPM on the signal and is similar to that presented in [6].

Two tunable external cavity lasers at 1539.28nm (signal) and 1539.60nm (pump) are arranged as close as possible to guarantee a strong influence of XPM. Each of these lasers is followed by two MZMs that are driven by decorrelated 2^7-1 pseudorandom binary sequences (PRBS). For CF-RZ-DPSK and RZ-ASK, the MZMs are driven as described in section 2. In case of RZ-ASK, the only difference is that the first MZM operates conventionally to form a NRZ-ASK signal. Signal and pump are copolarized, combined and amplified to an average power per channel of P_s=0dBm and P_p=15dBm, for signal and pump, respectively. This particular transmitter setup allows to measure power penalties that are caused exclusively by XPM. SPM and FWM do not give rise to a power penalty because the signal is transmitted with only P_s=0dBm [6].

The two channels are transmitted over 50km of uncompensated standard single mode fiber (SSMF). The fiber dispersion converts the XPM induced PM into an amplitude modulation (AM). This is similar to the case of residual dispersion in WDM systems that generally cannot be avoided. Only this AM causes system impairments while the pure PM does not because of the magnitude square law characteristic of the photodiode. Nevertheless, the link length of 50km ensures that the fiber dispersion does not yet cause the eye diagram to close.

By means of this experimental setup, it is possible to generate a strong impact of XPM on the signal. This single-span setup avoids to implement a loop experiment in which the impact of XPM is caused by the accumulated XPM contribution over several spans. On the other hand, it ensures that system penalties are measured and not just intensity fluctuations on an unmodulated probe signal [7].

After propagation, the signal is selected by a 0.2nm filter and sent to an optical preamplifier followed by a 2nm filter and a 7GHz electrical receiver. The receiver power at the preamplifier input at 10^{-9} bit-error rate (BER) is measured for the case that the pump channel is switched on and off, respectively. By means of this, the resulting power penalty induced by XPM only, is determined for both modulation formats.

The measured eye diagrams in **figs. 6-7** indicate strong distortions due to XPM for RZ-ASK whereas in the case of CF-RZ-DPSK, the eye diagram is similar to that measured in a single channel experiment over 50km SSMF in the linear regime.

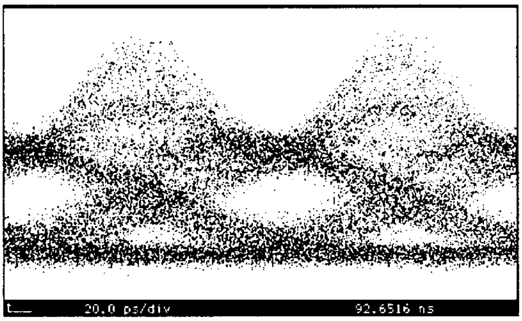

Fig. 6 Eye-opening for RZ-ASK in 2x10Gb/s over 50km uncompensated SSMF with $\Delta\lambda$=0.32nm, P_s=0dBm, P_p=15dBm (average power), with 7GHz electr. lowpass

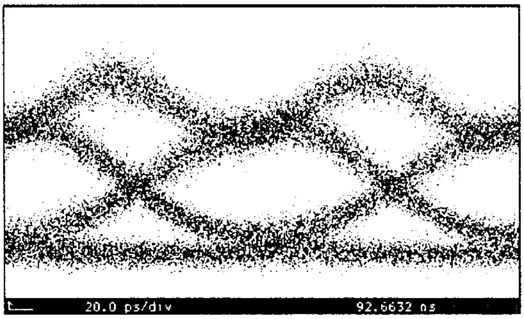

Fig. 7 Eye-opening for CF-RZ-DPSK in 2x10Gb/s over 50km uncompensated SSMF with $\Delta\lambda$=0.32nm, P_s=0dBm, P_p=15dBm (average power), with 7GHz electr. lowpass

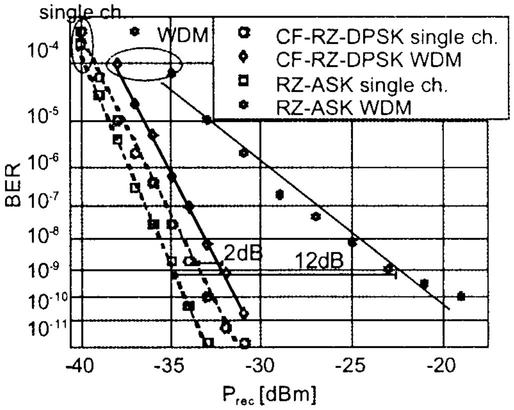

Fig. 8 XPM induced power penalty for CF-RZ-DPSK (<2dB) and RZ-ASK (>12dB) in 2x10Gb/s over 50km uncompensated SSMF with $\Delta\lambda$=0.32nm, P_s=0dBm, P_p=15dBm (average power); "single ch." and "WDM" corresponds to pump switched off and on, respectively

Finally, in **fig.8**, we show the resulting BER curves for RZ-ASK and CF-RZ-DPSK. In order to identify the influence of the XPM-effect, we compare a single channel (pump switched off) and the described two channel WDM experiment. For the case of single channel transmission the only signal distortion is caused by group velocity dispersion of 50km SSMF. With the copropagating pump channel the signal distortions are caused by GVD and XPM. Therefore, the resulting power penalty (by comparing single channel and WDM) indicates the signal distortions that are caused exclusively by XPM. We measured a power penalty in case of RZ-ASK of 12dB whereas for CF-RZ-DPSK only a penalty of 2dB is measured. Thus, the proposed CF-RZ-DPSK modulation scheme is a promising candidate for long-haul WDM transmission with close channel spacing.

5 Conclusion

We proposed CF-RZ-DPSK as a new modulation format to suppress the impact of XPM on long-haul DWDM systems over SSMF almost completely. Simulations and experiments confirm the excellent performance of CF-RZ-DPSK in XPM limited transmission setups.

6 Acknowledgment

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7 References

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