The Influence of FBG Phase Ripple Distortions - Comparison for Different Modulation Formats

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Abstract: We present a simulative investigation of the influence of phase ripple distortions of FBGs on different modulation formats. Statistical ripple characteristics emulate a realistic system setup.

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1. Introduction

In today's optical communication systems, dispersion compensating fiber Bragg gratings (DCFBGs) are a promising candidate to replace DCF (dispersion compensating fiber) with its strong attenuation and highly nonlinear transmission properties. DCFBGs overcome these disadvantages, but have imperfections in their group delay characteristics [1]. These group delay ripples (GDR) have different influences on the transmitted signal dependent on the modulation format and the pulse shape [2-4]. This influence can be investigated by regarding the phase response obtained from the GDR. The ripples have a statistical characteristic. They can be separated by Fourier analysis into several sinusoidal contributions (ripple spectrum). The system penalty induced by a sinusoidal ripple can be analytically determined [2], but it is difficult to predict the penalty induced by a complete ripple spectrum [5]. Hence, in this paper we investigate by statistical simulations how different modulation formats behave with multi frequency ripples. The ripples are taken from measurements of a state-of-the-art DCFBG for WDM transmission with separate pass bands for each WDM channel.

2. Determination of statistical multi frequency phase ripples and single frequency ripples

The multi frequency ripples are taken from a group delay measurement of a commercial DCFBG. The phase ripple characteristics are extracted by subtracting the linear part from the measured group delay characteristic over wavelength for one channel. The remaining GDR, which has a peak-to-peak ripple amplitude of 19 ps maximum, is integrated over the wavelength. To randomize the ripple influence, this characteristic is shifted cyclically with respect to the carrier frequency of the laser signal. With this method, a set of 100 different FBGs is modeled. These 100 FBGs are composed randomly together in 1000 different multi span links, each consisting of up to 20 FBGs.

The phase ripple of one FBG represented as the phase response $b(f)$ can be separated into different frequency components by Fourier series expansion [2]

$$b(f) = -\sum_{i=1}^{N} \Delta\tau_{g,i} f_{rip,i} \sin\left(\frac{2\pi f}{f_{rip,i}} + \varphi_{0,i}\right), \qquad (1)$$

where the $\Delta\tau_{g,i}$ are the group delay amplitudes, $f_{rip,i}$ the ripple frequency components and $\varphi_{0,i}$ the phase shifts relative to the carrier frequency of the laser signal. These three parameters determine the influence of the ripple on the signal. The sinusoidal phase distortion leads to pre and post curser echoes with temporal distance of n/f_{rip} to the main signal pulse and weighted by the Bessel function of the n-th order J_n as the impulse response (2) of a single frequency ripple device shows. The amplitude of the echo is real for a phase shift φ_0=0 and imaginary for φ_0= π/2.

$$h_0(t) = J_0(\Delta\tau_g f_{rip}) \cdot \delta_0(t) + \sum_{n=1}^{\infty} J_n(\Delta\tau_g f_{rip}) \cdot \left[\delta_0\left(t - \frac{n}{f_{rip}}\right) e^{jn\varphi_0} + (-1)^n \delta_0\left(t + \frac{n}{f_{rip}}\right) e^{-jn\varphi_0}\right] \qquad (2)$$

3. Simulation setup

The simulation setup with a data rate of 11 Gb/s is shown in Fig. 1. The considered modulation formats are amplitude shift keying (ASK), differential phase shift keying (DPSK), and differential quadrature phase shift keying (DQPSK) with non-return-to-zero (NRZ) and return-to-zero (RZ) pulse shapes, respectively, and optical duobinary (ODB). For the differential formats, balanced detection is applied. To focus on the influence of the ripples, we consider full compensation of dispersion and linear fiber. The receiver consists of a 100 GHz Gaussian optical filter and a photo diode, followed by an electrical 3rd order Butterworth filter with bandwidth 0.7x symbol rate for NRZ and 1.1x symbol rate for RZ. The received signal is evaluated after every second FBG. Since OSNR estimation for the enormous number of received signal wave forms (1000x10 for each modulation format) would take too much time, the eye opening penalty (EOP) as the ratio of the maximum opening of the disturbed eye and the eye without ripple influences is measured.

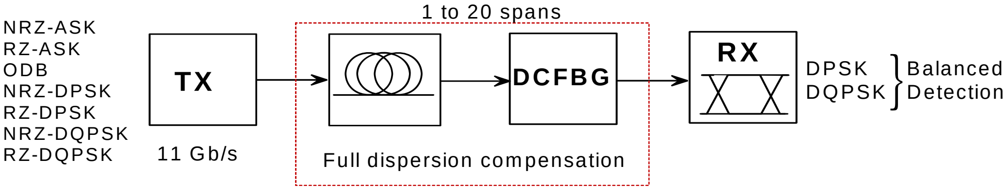

Fig. 1: Simulation setup. Linear fiber and full dispersion compensation are assumed. The signal is evaluated after every second span.

For single frequency ripple simulations the optical and the electrical filter are left out and only one FBG with sinusoidal ripples determined by $\Delta\tau_g$, f_{rip} and φ_0 is investigated.

4. Results and Discussion

Fig. 2 a) shows the mean EOP after 1 to 20 spans. Since we have simulated 1000 different setups a probability density function (PDF) of the EOP can be given as well. Fig. 2 b), c) show the PDFs of the EOP after 20 spans.

It can be seen that NRZ-ASK shows the smallest mean EOP, followed by RZ-ASK and NRZ-DPSK. RZ-DPSK and both DQPSK formats behave worse. In general, the NRZ pulse shape leads to slightly smaller EOPs except for ODB which achieves the highest penalty.

Since the mean EOPs do not show the spreading of the EOP for the 1000 setups the consideration of the PDF is important. For all RZ modulation formats the PDFs look very similar and spread out to 1.5 dB maximum. Differences appear for NRZ: NRZ-DQPSK and ODB are more sensitive to the special ripple setup than the other formats.

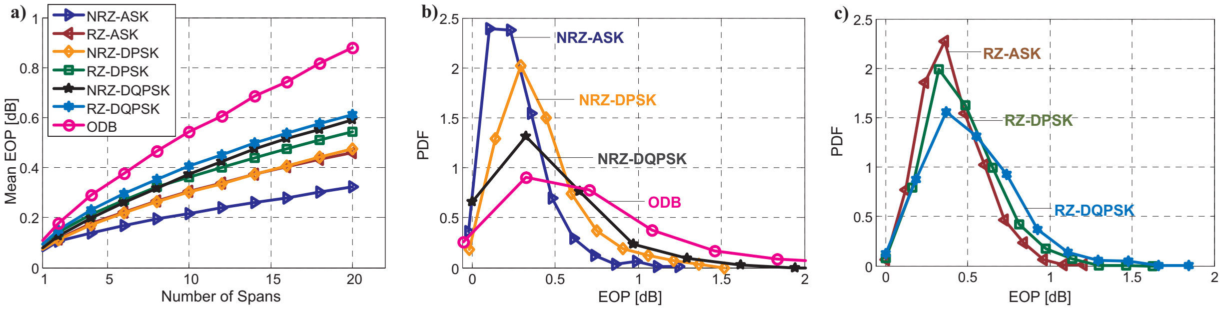

Fig. 2: a) Mean eye opening penalties for all investigated modulation formats after 1 to 20 spans with FBG dispersion compensation and statistical phase ripples. b), c): Normalized probability density functions of the eye opening penalty after 20 spans: b) NRZ modulation formats, c) RZ formats

Fig. 3 shows the EOP due to single frequency ripples for all modulation formats and different phase shifts φ_0 with $\Delta\tau_g$=20 ps. It can be seen that the cases, in which the signal is real, i.e. for ASK, DPSK and ODB, the worst distortion results from a phase shift $\varphi_0=0$. For DQPSK the worst distortion occurs at $\varphi_0=\pi/4$, which is the case of complex echoes with the same amplitude for real and imaginary part. In this case both, the in phase and the quadrature component of the DQPSK signal, are affected. Although the symbol rate for DQPSK is half the symbol rate of the other formats, its degradation is in the same order. The multi peak characteristics below the bit frequency for the RZ pulse shapes result from smaller interference times due to smaller time duration of the pulses.

The highest EOP for $\varphi_0=0$ can be observed at ripple frequencies around the bit frequency f_{bit} and half of f_{bit} for most modulation formats, because in these cases the echoes of the transmitted pulse are located directly in the next bit or the bit after the next. For increasing ripple frequencies and constant group delay, the echo amplitude increases and the echoes move into the actual bit. Since for $\varphi_0=0$ the first echoes have opposite sign, at one pulse edge the amplitude of the main pulse is increased, in the middle the echoes cancel out each other and at other edge the pulse is decreased. This leads to a time shift of the maximum eye opening and a decrease of the EOP. For some modulation formats, especially for RZ pulse shapes this leads to a negative penalty. The vertical eye opening is higher than without distortion, but the horizontal opening is very small. For ODB the worst case penalty is located at

f_{rip}=0.7f_{bit} – this results from the non-ideal shape of the three-level-format which is produced in our case by a low pass filter in the electrical domain.

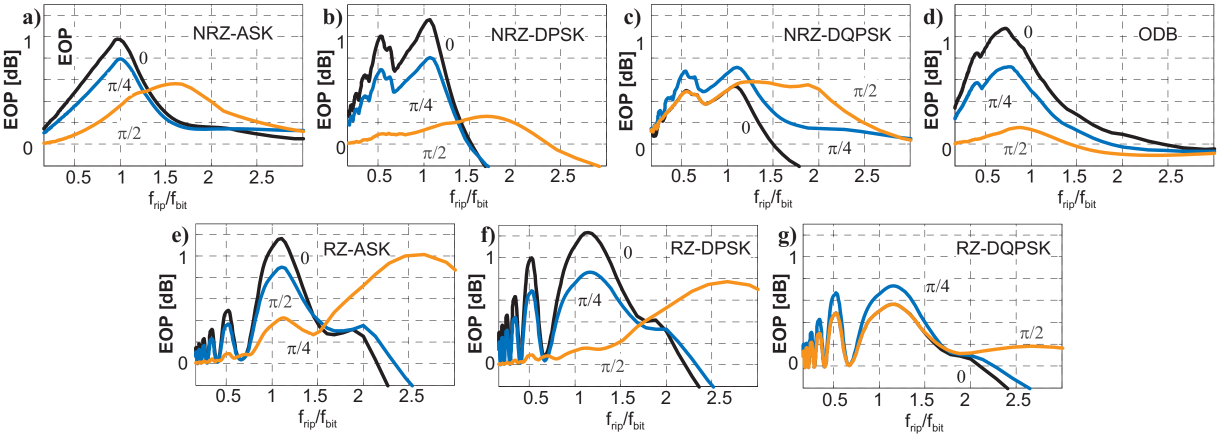

Fig. 3: Eye opening penalty introduced by single frequency phase ripples for all modulation formats. Ripple amplitude $\Delta\tau_g$=20 ps, phase shift φ_0=0, π/4, π/2: a) NRZ-ASK, b) NRZ-DPSK, c) NRZ-DQPSK, d) ODB, e) RZ-ASK, f) RZ-DPSK, g) RZ-DQPSK

For φ_0=π/2 both (imaginary) echoes have the same sign. The maximum penalty can be observed when the value of the first echo at the neighbouring bit slot center becomes maximal. For NRZ case this occurs at approximately 1.5f_{bit}. Since RZ pulses are narrower, the first echo can not affect neighbouring pulses and the effect is observed for the second echo at ripple frequencies of 2.5f_{bit}. Similarly, the much higher penalty for NRZ-DQSPK compared to RZ-DQPSK for frequencies between f_{bit} and 2f_{bit} can be explained. ODB is very tolerant towards symmetrical distortion of the impulse response, because the inter symbol interference of a 1 and a -1 surrounding a 0 cancel out each other. This can be observed at φ_0= π/2, where the distortion is symmetrical and the performance of ODB is much better than for the other modulation formats. The performance is worse for φ_0= 0, because the impulse response is asymmetrical. The echoes of the -1 and 1 that fall into the 0 have the same sign and are added up.

The single frequency results show that for the RZ pulse shape, in contrast to NRZ, two different ripple frequencies produce severe degradation, f_{rip}=f_{bit} for the φ_0=π/2 case and f_{rip}=2.5f_{bit} for φ_0=π/2. Therefore, RZ will perform a little worse in a statistical ripple environment. For NRZ-DQPSK the single frequency results show three different behaviours: For φ_0=0 the penalty is quite low, for φ_0= π/4 it is higher but in the same region as for RZ-DQPSK and for φ_0= π/2 it is much worse than for RZ-DQPSK. This leads to a similar statistical mean penalty for both pulse shapes, but the phase sensitivity of NRZ-DQPSK can be seen in the broad PDF in Fig 2. The broad PDF of ODB can also be explained by the very different behaviours for φ_0=0 and φ_0=π/2. The total penalty of ODB format is very sensitive to the phase shift between signal frequency and ripple characteristic.

5. Conclusion

We have compared different modulation formats and their robustness towards distortions resulting from phase ripples induced by dispersion compensating fiber Bragg gratings. Statistical investigation reveals that NRZ pulse shape shows superior behavior compared to RZ pulse shape for all formats except DQPSK. Moreover, we show that ODB is very sensitive to phase ripples. All results are explained by considering single frequency ripples.

6. References

[1] D. van den Borne et al.: "Cost-effective 10.7-Gbit/s Long-Haul Transmission using Fiber Bragg Gratings for In-line Dispersion Compensation, in Proc. OFC 2007, Paper OThS5

[2] C. Scheerer et al.: "Influence of Filter Group Delay Ripples on System Performance", in Proc. ECOC 1999, pp. I-410 f.

[3] T.N. Nielsen, et al.: "Penalties associated with Group Delay Imperfections for NRZ, RZ and Duo-Binary Encoded Optical Signals", in Proc. ECOC 1999, pp. I-388 f.

[4] X. Liu, et al.: "Impact of Group-Delay Ripple in Transmission Systems Including Phase-Modulated Formats", in IEEE Photonics Technology Letters, Vol.16, No.1, 2004, pp.305-307

[5] J.-P. Elbers, C. Fürst: "Group-Delay Ripple Induced Performance Degradation in Optical DQPSK Transmission", in Proc. ECOC 2006, Paper We3.P.107

[6]H. Bissessur et al.: "Performance Characterization of Components with Phase Ripple for Different 40 Gb/s Formats", in Proc. OFC 2006, Paper OFN4