Electronic Equalization of FBG Phase Ripple Distortions in 43 Gb/s WDM Systems

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Abstract

Within this paper we investigate in a first step the transmission performance for a 43-Gb/s wavelength division multiplex (WDM) system with channelized and broadband fiber Bragg gratings (FBGs) for dispersion compensation by statistical simulations. The results demonstrate the feasibility and limitations of replacing dispersion compensating fiber (DCF) in 43 Gb/s systems by FBGs and of upgrading a 10.7 Gb/s system with FBG dispersion compensation to 43 Gb/s. Phase ripple distortions and the narrow band filtering of the channelized FBG extend the OSNR requirements or lead to reduced possible transmission lengths. To overcome these limitations, linear feed-forward-equalizers (FFE), combinations of feed-forward and decision-feedback (FFE-DFE) equalizers, and nonlinear FFE-DFEs are introduced. We show that the OSNR penalty due to filtering and ripples can be significantly reduced by using nonlinear equalizers. Investigated modulation formats are NRZ-ASK (amplitude shift keying with non-return-to-zero pulse shape) and optical duobinary (ODB).

1 Introduction

Recent developments make dispersion compensating fiber Bragg gratings suitable not only for adjustment of the residual dispersion of a transmission system, but also for inline compensation after every transmitted span [1]. In contrast to dispersion compensation fiber (DCF) they offer a low insertion loss, negligible nonlinearities and cost effective production. Two types of FBGs are available for this purpose. The channelized short one introduces in addition to the linear group delay for dispersion compensation an amplitude band pass filtering to each WDM channel. The longer broadband FBG offers a constant insertion loss over the total transmission band for all channels. The main drawback of using FBGs for dispersion compensation is the imperfection of the group delay characteristic and therefore phase response, expressed in group delay ripples or phase ripples [2]. After transmission over several spans the influence will add up and lead to additional system penalty. The penalty is dependent on modulation format, pulse shape and FBG type [3]. Also interactions between phase ripples and fiber nonlinearities have to be considered. For the channelized FBG the filtering of each WDM channel has also a severe influence if the signal bandwidth is broader than the FBG pass band.

In this paper we show the results of extensive statistical simulations on transmission penalties of the two FBG types for conventional on-off-keying (NRZ-ASK) and optical duobinary (ODB) at 43 Gb/s WDM transmission. Since phase ripples and amplitude filtering lead to system degradation, we introduce electronic equalization to improve the received signal. It has been shown that electronic equalization can overcome many impairments that occur during the optical transmission, such as chromatic dispersion and fiber nonlinearities [4-6]. In [7] electronic equalization is used to mitigate distortion due to phase ripples in a linear system with sinusoidal phase ripples. Since the results are promising, we here introduce different types of fractionally spaced (two samples per bit) linear and non-linear equalizers and show their capability of reducing the OSNR penalty and increasing the possible transmission length in a phase ripple distorted WDM transmission system with narrow band amplitude filtering and nonlinear fiber.

2 Simulation Setup without Equalization

The simulation setup without equalization is shown in **Fig. 1**. To account for inter channel nonlinearities five WDM channels with a channel spacing of 100 GHz are transmitted over up to 20 spans of standard single mode fiber (SSMF). The input power to the fiber is varied from -3 to 3 dBm per channel. Both FBG types (here referred to by FBG A/B) are used to compensate for the dispersion of the span, including dispersion slope. The 3-dB-bandwidth of the channelized FBGs is approximately 65 GHz, which is a typical value for this type of FBG. An EDFA is used to compensate for the loss of the fiber. At the receiver side the five channels are demultiplexed and the BER (Bit Error Rate) of the center channel is evaluated. By evaluating the eye diagram, the residual dispersion is optimized. The OSNR at a BER of $5\cdot 10^{-4}$ is estimated by a χ^2-distribution based method [9] after every second span. Since the ripple characteristic (for the channelized FBG also the amplitude characteristic) varies from FBG sample to FBG sample, statistical investigations are necessary to get a general valid result for the expected penalty. For this reason, FBG phase and frequency responses are extracted from group delay and insertion loss measurements of approximately 100 FBGs per type. Out of these, 20 different combinations of 20 FBGs each are chosen randomly for the 20 transmission spans. For each combination three different wavelengths are chosen for the center channel of the five WDM channels, one at each side of the transmission band and one in the middle. This results in 60 different FGB transmission setups per FBG type (20 combinations x 3 channels). The same combinations are investigated for both modulation formats, NRZ-ASK and ODB. The ODB signal is generated by lowpass filtering of the precoded binary signal in the electrical domain.

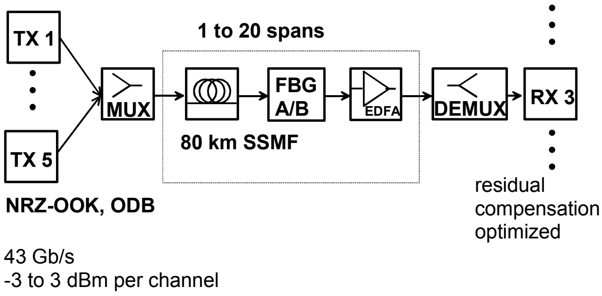


Fig. 1 Simulation setup. Five WDM channels at 43Gb/s are transmitted over up to 20 spans of SSMF. Channelized and broadband FBGs (here demarked as A and B) are used to compensate for the dispersion, respectively.

3 Results without Equalization

Fig. 2-4 show the mean OSNR penalty normalized to the back-to-back OSNR without any transmission. The mean is taken over the 60 OSNR penalty results for the 60 setups of channelized FBGs. It is plotted vs. number of transmitted spans for both modulation formats and fiber input powers of -3 dBm, 0dBm and 3 dBm, respectively. For NRZ-ASK the penalty increases strongly after few spans. For -3 dBm the maximum transmission length is limited to 8 spans for some setups. This results in a required OSNR of infinity. In interaction with fiber nonlinearity at 0 dBm and 3 dBm the BER of $5{\cdot}10^{-4}$ is not achievable for all setups any more after 6 spans. It can be concluded that the narrowband filtering together with stronger phase ripples at the edges of the pass band have a severe influence on this format because of its broad signal spectrum. Therefore the channelized FBG is not suitable for 43 Gb/s NRZ-ASK transmission without additional equalization. For ODB at all input powers first a slight improvement due to the filtering [10] can be observed. Afterwards the penalty increases mainly induced by phase ripples, since ODB is much more sensitive to phase ripples than other modulation formats. However, due to the narrow spectrum it suffers less from the amplitude filtering. For increased input power the transmission distance in decreased because of fiber nonlinearity and its interaction with phase ripples.

Since the mean OSNR penalty does not give a clear overview over all setups, **Fig. 5** shows the normalized probability density functions (PDF) of the required OSNR at a BER of $5{\cdot}10^{-4}$ after the maximum number of spans for both formats. It can be seen that especially for higher input powers the spread is very wide for ODB. For NRZ-ASK it is very similar for all powers. This shows that the penalty mainly results from the amplitude filtering.

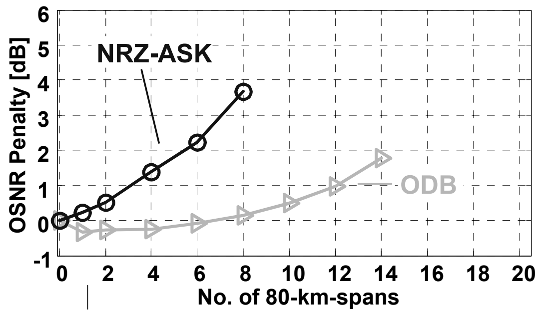


Fig. 2 OSNR penalty vs. number of spans for channelized FBG, -3 dBm / span.

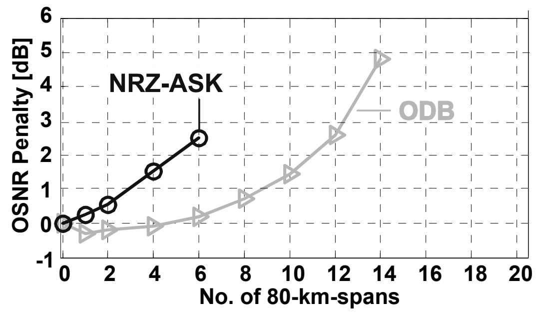


Fig. 3 OSNR penalty vs. number of spans for channelized FBG, 0 dBm / span.

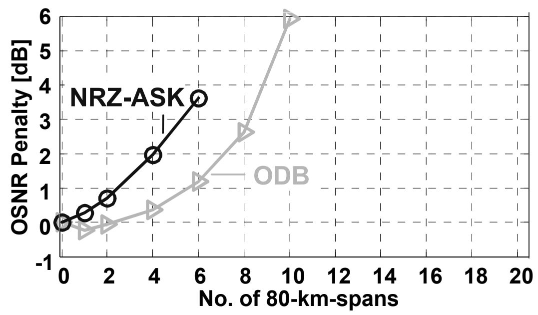


Fig. 4 OSNR penalty vs. number of spans for channelized FBG, 3 dBm / span.

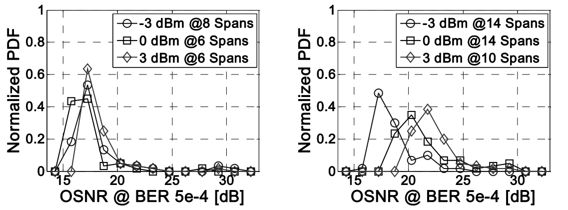


Fig. 5 Normalized probability density function of required OSNR after maximum number of spans for channelized FBG at different input powers. Left: NRZ-ASK, right: ODB.

Fig. 6-8 show the results for the broadband FBGs at different input powers. Both formats show much better performance. In case of NRZ-ASK, this mainly results from the absence of amplitude filtering. However, also the more equal distribution of the ripples over the whole FBG transmission band (in contrast to the strong ripples at the edges of the pass bands for the channelized FBG) and therefore smaller mean ripples lead to good transmission results for the broad signal spectrum. The latter property also explains the better performance of the broadband FBG for the very ripple sensitive format ODB. Although the mean OSNR penalties for NRZ-ASK and ODB are very similar, the normalized PDFs in **Fig. 9** show that the spread of the penalty is wider for NRZ-ASK than for ODB.

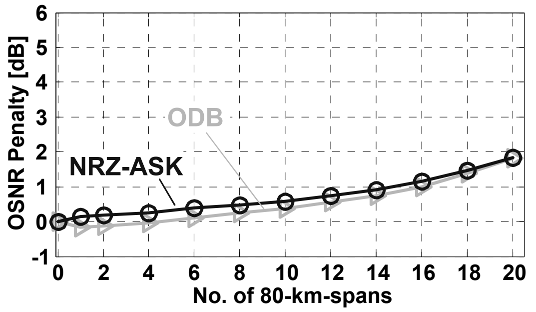


Fig. 6 OSNR penalty vs. number of spans for broadband FBG, -3 dBm / span.

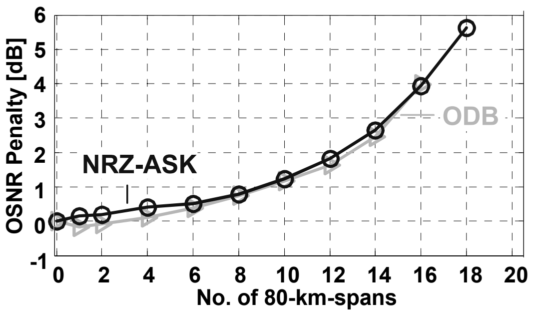


Fig. 7 OSNR penalty vs. number of spans for broadband FBG, 0 dBm / span.

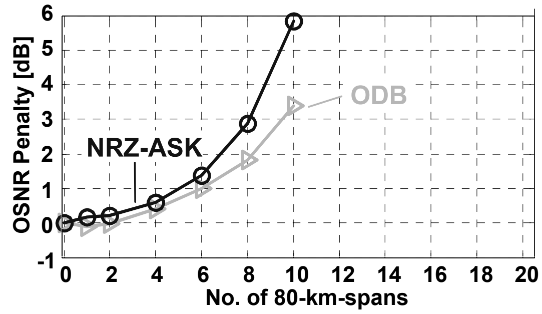


Fig. 7 OSNR penalty vs. number of spans for broadband FBG, 0 dBm / span.

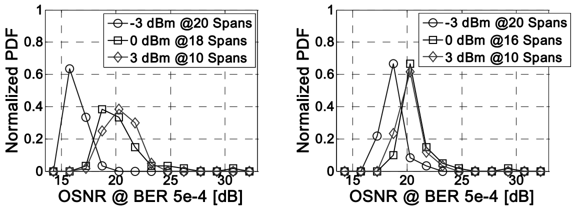


Fig. 9 Normalized probability density function of required OSNR after maximum number of spans for broadband FBG at different input powers. Left: NRZ-ASK, right: ODB.

The results of these simulations show that the channelized FBG in this configuration is not suitable for NRZ-ASK since the broad spectrum is affected too much by the narrowband filtering and the stronger phase ripples at the edges of the pass bands. In contrast to that, ODB shows a good performance up to 10 spans (800 km) at low input power.

The broadband FBG is very suitable for both modulation formats. Moreover, both formats show nearly the same performance. For higher input powers a limitation due to fiber nonlinearity and interaction of nonlinearity and phase ripples can be observed.

4 Simulation Setup with Equalization

In this section we introduce electronic equalization to overcome the degrading influence of the phase ripples and the amplitude filtering. In [7] several FFE and FFE-DFE combinations have been tested to equalize phase ripple distortions. The NL(3,2)-FFE(4)-DFE(2) equalizer showed very good performance. In order to keep the implementation effort small, we try a linear FFE(8) (8 delay tap FFE) and a FFE(8)-DFE(4) (8 delay tap FFE and 4 delay tap DFE) at first. Afterwards we will use a NL(3,2)-FFE(4)-DFE(2) (4 delay tap FFE and 2 delay tap DFE with nonlinear order 3 and 2 for FFE and DFE, respectively) and a NL(3,2)-FFE(8)-DFE(4) (8 delay tap FFE and 4 delay tap DFE with nonlinear order 3 and 2 for FFE and DFE, respectively). The structures of the equalizers and the mathematical description can be found in [11] and [12]. All equalizers use an oversampling of 2. The coefficients are determined using the minimum mean-square error rule. Since in [7] no nonlinear fiber influences are taken into account and in [5] the capability of electronic equalization to cancel out distortions due to nonlinearities is shown, it will be investigated here, if equalization will also work for distortion resulting from interaction of nonlinearities and phase ripples.

Our previous BER results were taken by an estimation method. This method cannot be used for estimation of error rates after nonlinear equalizers. Therefore, we need to evaluate the BER by Monte Carlo simulations. Monte Carlo simulations take much more time than the estimation. Due to this, statistical simulations are not possible anymore. We now pick out the two FBG combinations with the worst results for each FBG type, modulation format and input power. For these combinations Monte Carlo simulations without equalizer and with all equalizer types are performed. Since the results for both worst FBG combinations are similar, only one is shown. It is assumed that if the equalization will work for a very badly distorted signal, it will also work for a less distorted signal.

The setup of the simulation system is exactly the same as in Fig. 1. The only change is an additional equalization block to equalize the distorted signal of the center channel.

5 Results with Equalization

The OSNR performance for NRZ-ASK with one of the most critical channelized FBG combinations is shown in **Fig. 10**. The pass bands of some of the FBGs are shifted against each other, whereby the resulting bandwidth after a cascade of several FBGs can be reduced down to 55 GHz. This leads to the very bad performance for the required OSNR at a BER of $5 \cdot 10^{-4}$ even for small input powers of -3 dBm. Moreover, higher input powers have negligible influence on the OSNR performance. The introduction of a linear FFE does not cause much improvement. However, the additional feedback filter within the FFE(8)-DFE(4) allows a transmission over the maximum investigated number of 20 spans in the case of -3 dBm input power. The penalty after 20 spans is 9 dB. This value can be improved by using the NL(3,2)-FFE(4)-DFE(2) or the NL(3,2)-FFE(8)-DFE(4) to 7 dB or 5 dB, respectively. However, if less than 20 spans are considered, the additional effort using more equalizer coefficients and nonlinear structures seems not necessary since the differences in the OSNR penalty are not high. For higher input power the NL-FFE-DFE shows better performance than the FFE-DFE and an increased number of coefficients leads to improved equalization.

The results for the broadband FBG are shown in **Fig. 11**. For small input powers all equalizers perform similar. Equalization leads to an OSNR improvement of 2 dB after 20 spans. For higher input power the fiber nonlinearity increases and equalizers with more nonlinearity show better performance. If the results are compared to those for the channelized FBG, it can be concluded that the effort to equalize amplitude filtering is much smaller than that for fiber nonlinearities in interaction with phase ripples. For higher input powers, the NL-FFE-DFE with increased number of coefficients shows an extremely good performance. This results from the fact, that the main degrading effect is fiber nonlinearity, which can be mitigated excellently via the NL-FFE-DFE with sufficient coefficients.

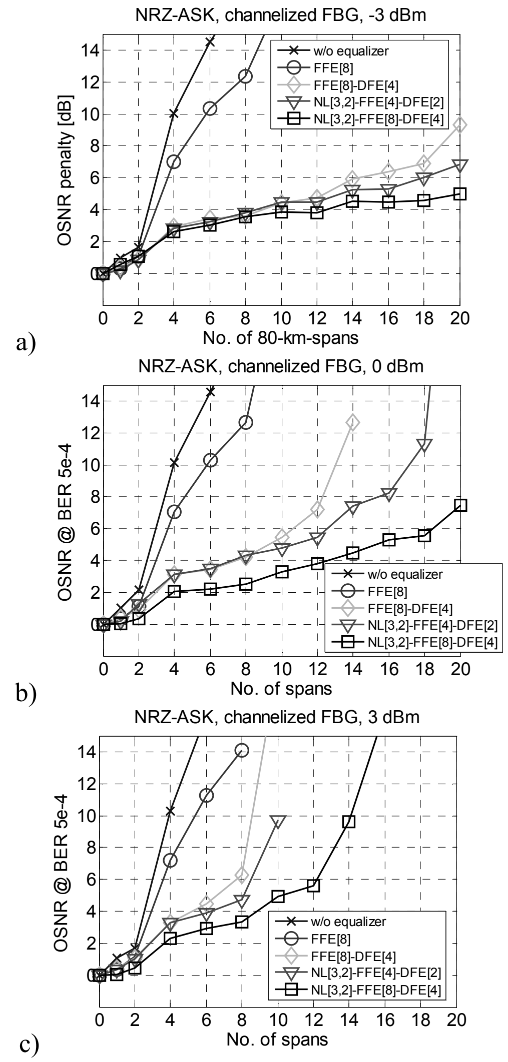


Fig. 10 OSNR penalty vs. number of spans without equalization and for different equalizer setups. NRZ-ASK, channelized FBG.:
a) -3 dBm / span, b) 0 dBm / span, c) 3 dBm / span.

The results for ODB are presented in **Fig. 12** for the channelized FBG and in Fig. 13 for the broadband FBG. The OSNR penalty and the maximum possible transmission distance are much better than for NRZ-ASK if we consider no equalizer. However, with the use of a FFE or FFE-DFE nearly no improvement can be observed for both FBG types and all considered input powers. This is due to the fact, that the ODB format offers a special tolerance to distortion with symmetrical inter symbol interference (ISI), such as chromatic dispersion. Phase ripples can cause asymmetrical distortions, which leads to an increased sensitivity of ODB towards the ripples [3,13]. Due to the same reason, the degradation of a received 0 and a received 1 resulting from a duobinary signal suffer from different amount of ISI. This effect, in [7] referred to as "nonlinear enhancement", is explained in detail in [8]. It limits the performance gain due to electronic equalization for ODB.

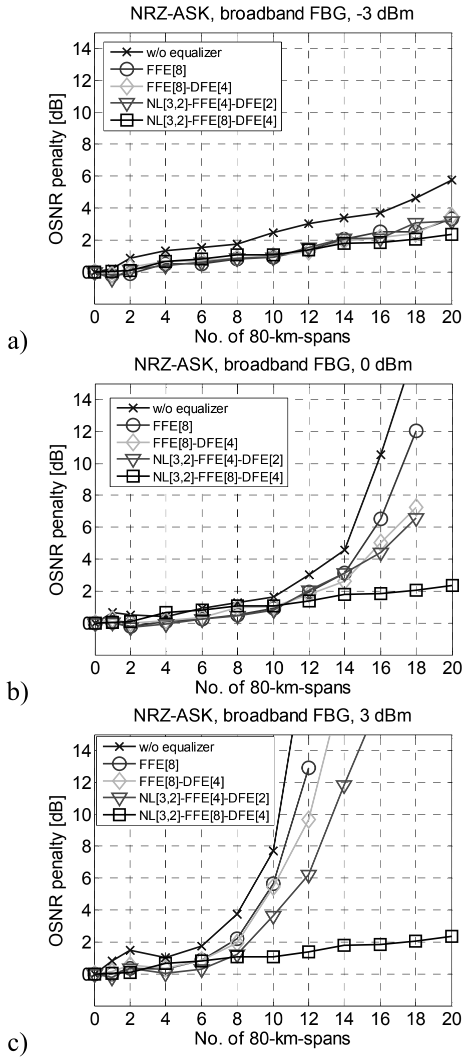


Fig. 11 OSNR penalty vs. number of spans without equalization and for different equalizer setups. NRZ-ASK, broadband FBG:
a) -3 dBm / span, b) 0 dBm / span, c) 3 dBm / span.

According to **Fig. 12** both NL-FFE-DFEs show a small capability to improve the signal. For -3 dBm input power the transmission distance can be increased to 20 spans, but an additional OSNR margin of 10dB for the NL[3,2]-FFE[4]-[2] and 6 dB for the NL[3,2]-FFE[8]-[4] has to be supplied, respectively, in comparison to the back-to-back case. For higher input powers the NL-FFE-DFEs show again a possible reduction of the required OSNR by some dB at a fixed transmission length or an increase of the transmission length of 2-6 spans at a fixed OSNR.

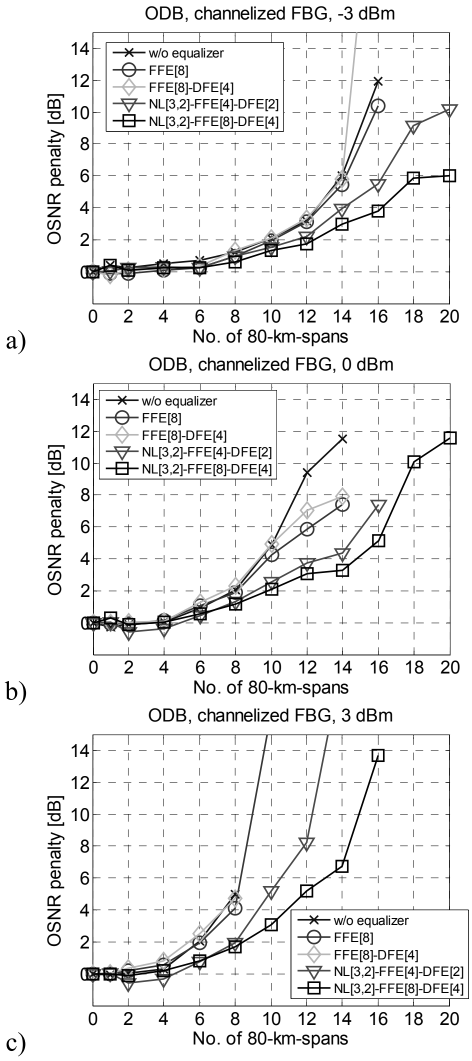
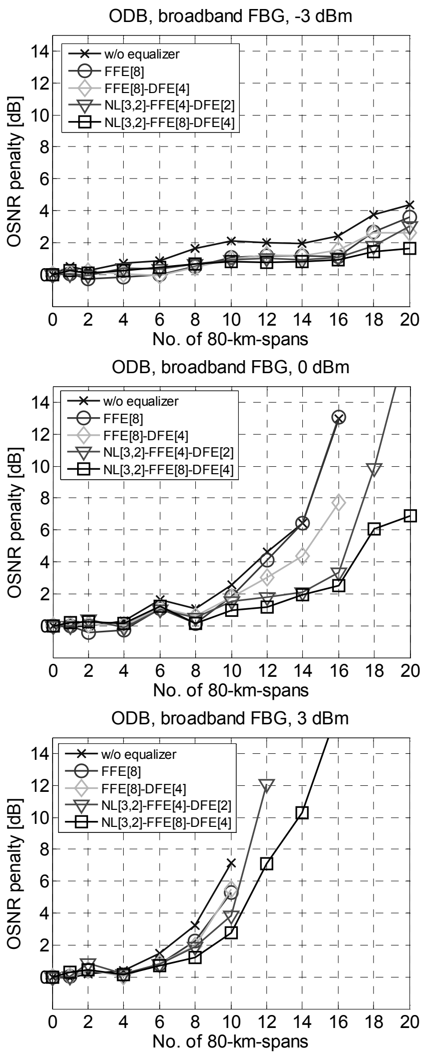


Fig. 12 OSNR penalty vs. number of spans without equalization and for different equalizer setups. ODB, channelized FBG:
a) -3 dBm / span, b) 0 dBm / span, c) 3 dBm / span.

The results for the broadband FBGs and low input power in **Fig. 13** a) show that a small improvement with all equalizers is possible. Thus we can conclude, that the small ripples, which are nearly equally distributed over the whole broadband FBG passband do not cause as severe asymmetrical ISI as the varying ripples of the channelized FBG.. If more fiber nonlinearity is present, the nonlinearity enhancement increases and the performance improvement by the FFE and the

FFE-DFE is lost. However, for 0 dBm input power, we can observe a good OSNR improvement for both NL-FFE-DFEs. At higher input powers the equalization only gives a small improvement.



a)
b)
c)

Fig. 13 OSNR penalty vs. number of spans without equalization and for different equalizer setups. ODB, broadband FBG:
a) -3 dBm / span, b) 0 dBm / span, c) 3 dBm / span.

6 Conclusion

In a first step we compared the performance of channelized and broadband FBGs for inline dispersion compensation in optical long-haul WDM transmission systems at 43 Gb/s. With the help of extensive statistical simulations we showed that typical channelized FBGs with a mean bandwidth of 65 GHz are not suitable for the transmission of NRZ-ASK signals at 43 Gb/s without additional equalization. However, for ODB by this FBG type shows sufficient performance for up to 800 km (10 spans). The broadband FBG shows very good transmission characteristics for both modulation formats. With increased input power to the fiber the transmission distance decreases due to fiber nonlinearities and their interaction with phase ripples.

Secondly, we applied electronic equalization to reshape the ripple and nonlinearity distorted signal. For NRZ-ASK a high improvement can be observed for both FBG types, especially if NL-FFE-DFE equalizers are applied. Thus it can be concluded, that if nonlinear equalization is available, both FBGs can be used for NRZ-ASK transmission at 43 Gb/s. For ODB the equalization shows less improvement due to the nonlinearity enhancement which results in the special properties of the ODB signal. Nevertheless, nonlinear equalizers can improve the possible transmission distance for ODB about approximately 2-6 spans if the input power per span is kept sufficiently low.

7 References

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