© Urban & Fischer Verlag
http://www.urbanfischer.de/journals/aeue

AEÜ International Journal of Electronics and Communications

Optimal Equalization of Distortions due to Group Delay Ripples of Chirped Fiber Bragg Gratings (CFBG)

Jan Mietzner, Sven Otte, Marc Bohn, Christoph Glingener and Werner Rosenkranz

Abstract **We present a closed solution for an optimal equalizer which compensates for signal distortions caused by group delay ripples in chirped fiber Bragg gratings (CFBG) employed for dispersion compensation in optical communication systems. The theory is verified with the help of group delay measurement results of a dispersion compensating CFBG and the improvements achieved by the equalizer are presented on the basis of simulation results.**

Keywords **Equalization, Group delay ripples, Dispersion compensation, Chirped fiber Bragg grating (CFBG)**

1. Introduction

The dramatically growing demand for data transport over optical networks forced higher single channel data rates and an increasing number of channels in wavelength-division multiplex (WDM) backbone systems. In this context, from an economic point of view, it is of particular interest to realize 40 Gb/s channels utilizing already installed fiber.

Usually standard-single-mode fibers (SSMF) are used in optical communication systems, especially in wide area networks (WAN). SSMF show chromatic dispersion, which corresponds to an approximately linear wavelength dependence of the group delay for light waves propagating along the fiber. As optical pulses used for data transmission contain a bunch of different wavelengths they therefore experience a broadening in the time domain. Especially in long fibers and in multi-span systems without 3R-regeneration (amplitude, clock and data recovery in the electrical domain) this can lead to a non-tolerable bit error rate (BER) due to intersymbol interference (ISI). Therefore in general dispersion and dispersion slope compensation is inevitable.

In order to eliminate the chromatic dispersion a cascade system of SSMF and dispersion compensating fiber (DCF) can be built. Alternatively, dispersion compensating chirped fiber Bragg gratings (CFBG) can be employed in the cascade system. In both cases a total cancellation of the dispersion within the cascade system can be achieved, which complies with a constant group delay.

The application of CFBG features several advantages compared to the DCF as for example a smaller signal attenuation [1]. Moreover, CFBG are more compact and do not suffer from nonlinear effects. At the same time, however, they are characterized by a fabrication induced non-ideal phase response [2]. This leads to variations within their group delay (referred to as *group delay ripples*) which cause additional signal distortions [3] and limits the total optical transparent length of a link [4]. CFBGs are promising elements if it is possible to minimize the influence of the group delay ripples. In [5] the transmission range is increased by using CFBG which show small group delay ripples, employing a special fabrication process presented in [6].

In this paper an alternative approach is investigated. First of all a closed analytical theory is presented which describes the signal distortions caused by group delay ripples in a CFBG. The theoretical considerations lead to the derivation of an optimal equalizer which totally compensates for the signal distortions due to the non-ideal group delay characteristic of the CFBG. In the case of complete dispersion compensation a cascade system consisting of SSMF, CFBG and optimal equalizer will show a constant group delay and the additional signal distortions are cancelled. The optimal equalizer may be realized as integrated device by means of an optical transversal filter in planar lightwave circuit (PLC) technology.

In Section 2 a model for the group delay ripples and the resulting signal distortions is developed on the basis of measurements within a dispersion compensating CFBG. In Section 3 the closed solution for the optimal equalizer is derived and in Section 4 simulation results are shown in order to verify the design of the equalizer. In Section 5 the results of this paper are summarized.

2. Model for the group delay ripples

In order to fabricate a dispersion compensating CFBG the phase mask employed to write the structure of the grating is linearly chirped. Due to this it is accomplished that the resulting group delay characteristic of the CFBG is a linear function of the wavelength with negative slope. Material properties and a non-ideal fabrication process result in the fact, that the linear characteristic is distorted which is referred to as *group delay ripples*. As an example

Received June 26, 2001.

Jan Mietzner, Sven Otte, Marc Bohn, Werner Rosenkranz, Chair for Communications (LNT), Faculty of Engineering, University of Kiel, Kaiserstrasse 2, 24143 Kiel, Germany.
Phone: +49 431-880-6301, Fax: +49 431-880-6303.
E-mail: wr@tf.uni-kiel.de
Christoph Glingener, Siemens AG, ICN, 81359 Munich, Germany.
Correspondence to Sven Otte.

1434-8411/02/56/3-187 $15.00/0

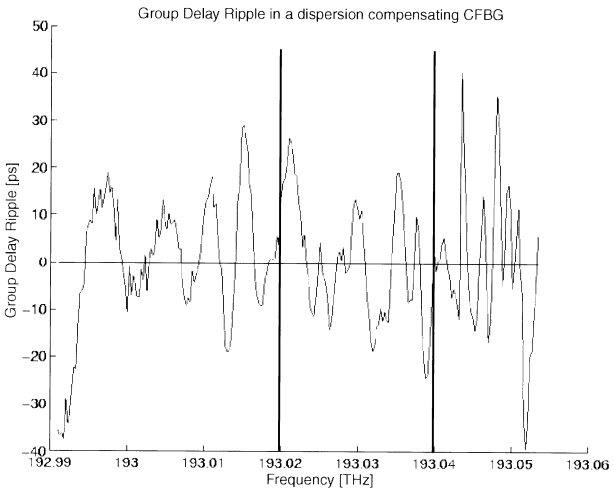


Fig. 1. Group Delay Ripples according to a Measurement in a dispersion compensating CFBG.

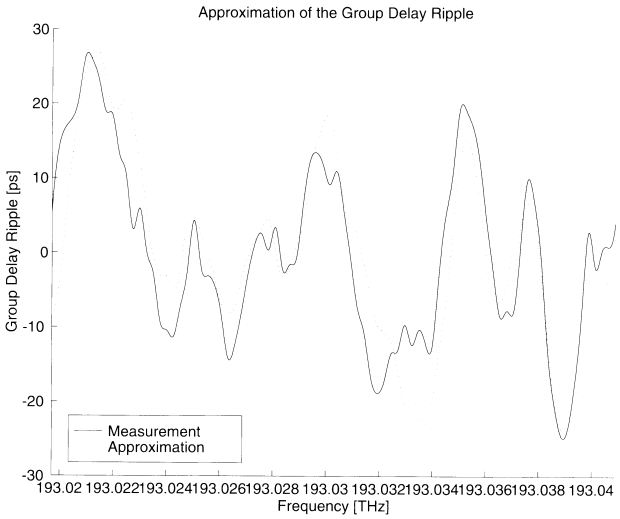


Fig. 2. Approximation of the Measured Group Delay Ripples using a sum of Cosine functions.

Fig. 1 shows group delay ripples in a CFBG as a function of the absolute frequency as observed in a measurement. The vertical lines mark the boundaries of a single channel of 20 GHz bandwidth within the third optical window, which is considered in the derivations below.

When we assume that the chromatic dispersion brought in by the SSMF is completely compensated using a CFBG with an ideal phase response, then the group delay of the cascade system of SSMF and CFBG is constant. Therefore, when regarding a non-ideal CFBG the group delay ripples of the grating can be regarded as the group delay characteristic of the entire cascade system.

In order to develop a model for the occurring distortions due to the non-ideal group delay $\tau_{\text{casc}}(f)$ of the cascade system a band in the third window is regarded. Within the regarded band it is possible to approximate the group delay by a sum of $N < \infty$ Cosine functions:

$$\tau_{\text{casc}}(f) = -\sum_{i=1}^{N} \Delta\tau_i \cos\left(2\pi f / f_{\text{ripple},i} + \varphi_i\right). \quad (1)$$

Each of the $i \in \{1, \ldots, N\}$ used Cosine functions shows an amplitude $\Delta\tau_i$, a period $f_{\text{ripple},i}$ and an angular offset φ_i.

Integration of $\tau_{\text{casc}}(f)$ leads to the phase response $\phi_{\text{casc}}(f)$ and thus to the transfer function $H_{\text{casc}}(f)$ of the cascade system. It is

$$\begin{aligned} H_{\text{casc}}(f) &= \mathrm{e}^{-\mathrm{j}\phi_{\text{casc}}(f)} \\ &= \prod_{i=1}^{N} \mathrm{e}^{\mathrm{j}\Delta\tau_i f_{\text{ripple},i} \sin\left(2\pi f / f_{\text{ripple},i} + \varphi_i\right)} \\ &= \prod_{i=1}^{N} H_i(f). \end{aligned} \quad (2)$$

Each of the N factors $H_i(f)$ is associated with a partial impulse response

$$\begin{aligned} h_i(t) = {} & J_0(\Delta\tau_i f_{\text{ripple},i})\, \delta_0(t) \\ & + \sum_{k=1}^{\infty} J_k(\Delta\tau_i f_{\text{ripple},i}) \Big[\delta_0\left(t - k/f_{\text{ripple},i}\right) \mathrm{e}^{\mathrm{j}k\varphi_i} \\ & + (-1)^k \delta_0\left(t + k/f_{\text{ripple},i}\right) \mathrm{e}^{-\mathrm{j}k\varphi_i} \Big], \end{aligned} \quad (3)$$

where $J_k(x)$ denotes the Bessel function of the first kind of order k and $\delta_0(t-x)$ is a Dirac impulse at $t = x$ [3].

Finally, the impulse response of the cascade system can be obtained by a multiple convolution of the partial impulse responses $h_i(t)$:

$$h_{\text{casc}}(t) = h_1(t) * h_2(t) * \ldots * h_N(t). \quad (4)$$

The measured group delay ripples of Fig. 1 have been approximated in the regarded band of the third window using a sum of $N = 19$ Cosine functions according to (1). The values for the amplitudes $\Delta\tau_i$, the periods $f_{\text{ripple},i}$ and the angular offsets φ_i have been obtained with the help of a Fast Fourier Transform (FFT) of the measured group delay ripples which is referred to as *ripple spectrum*. Fig. 2 shows the result of the approximation within the regarded band.

The values of $\Delta\tau_i$, $f_{\text{ripple},i}$ and φ_i employed in the approximation of the group delay have been used in order to calculate the impulse response $h_{\text{casc}}(t)$ of the cascade system of SSMF and CFBG according to (4).

3. Optimal equalization

In this section we derive the optimal equalizer for cancellation of the group delay ripple distortions described in Section 2 assuming complete dispersion compensation.

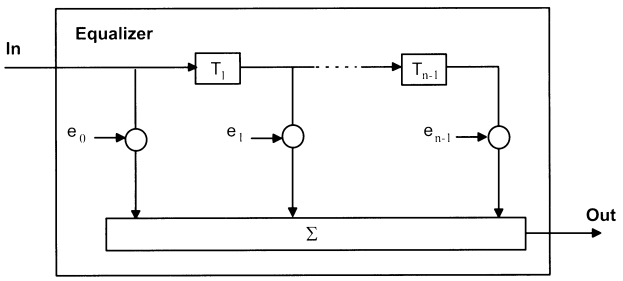


Fig. 3. Block Diagram of the Equalizer.

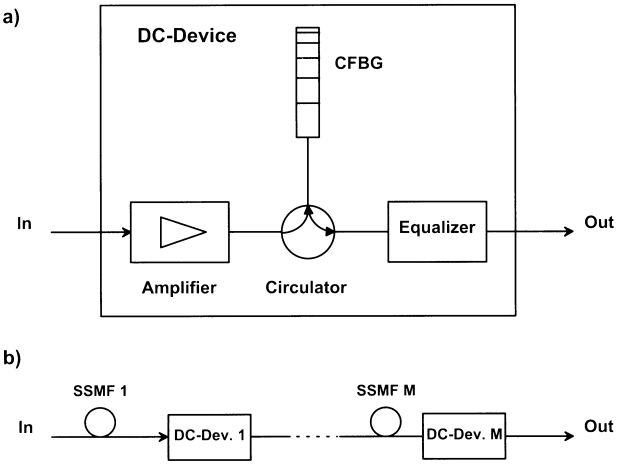


Fig. 4. Proposed Dispersion Compensating Device including a Group Delay Ripple Equalizer b) Potential Application of the Device in a Multi-Span System.

The optimal equalizer $E^{(\mathrm{opt})}(f)$ can be identified as the inverse system of $H_{\mathrm{casc}}(f)$ according to (2), because in the case of optimal equalization the transfer function of the cascade system of SSMF, optical filter and equalizer has to be 1 (i.e. total cancellation of ISI, neglecting delays):

$$H_{\mathrm{casc}}(f)\, E^{(\mathrm{opt})}(f) \doteq 1. \tag{5}$$

According to (2) and (5) we obtain

$$\begin{aligned} E^{(\mathrm{opt})}(f) &= \prod_{i=1}^{N} \mathrm{e}^{-\mathrm{j}\Delta\tau_i f_{\mathrm{ripple},i} \sin\left(2\pi f / f_{\mathrm{ripple},i} + \varphi_i\right)} \\ &= H^{*}_{\mathrm{casc}}(f), \end{aligned} \tag{6}$$

where $H^{*}_{\mathrm{casc}}(f)$ denotes conjugation of the complex transfer function $H_{\mathrm{casc}}(f)$.

Transfer of (6) to the time domain leads to the impulse response $e^{(\mathrm{opt})}(t)$ of the optimal equalizer (refer to (4)):

$$e^{(\mathrm{opt})}(t) = h^{*}_{\mathrm{casc}}(-t). \tag{7}$$

Therefore the optimal equalizer is a *Matched Filter* to the cascade system of SSMF and dispersion compensating CFBG. This result is as well valid in the case where the chromatic dispersion of the SSMF is not completely compensated by the CFBG.

According to (4) $h_{\mathrm{casc}}(t)$ consists of an infinite number of coefficients. Therefore in practice it is necessary to choose a finite subset of coefficients $\{e_0, \ldots, e_{n-1}\}$ in order to design the impulse response of the equalizer (t_i is the delay associated with coefficient e_i with respect to e_0):

$$e(t) = \sum_{i=0}^{n-1} e_i\, \delta_0(t - t_i), \tag{8}$$

The structure of the equalizer according to (8) complies with an FIR filter (*finite impulse response*). It is illustrated as a block diagram in Fig. 3, where T_i is the delay between the taps for the coefficients e_{i-1} and e_i.

The FIR structure of the equalizer can in principal be realized in form of a PLC, where it is possible to generate filter coefficients e_i showing arbitrary complex values [7].

Fig. 4 shows our proposal for a dispersion compensating device employing a CFBG and an appropriate equalizer, including an optical amplifier for loss compensation. Moreover, a potential application of the device in a multi-span system is shown leading to an increase of the total optical transparent length of a link (refer to Section 4).

4. Simulation results

In simulations we only took into account 4 coefficients of the optimal equalizer located at each side of the main impulse of $e^{(\mathrm{opt})}(t)$ which leads to an equalizer with $n = 9$ coefficients (refer to Fig. 3, T_i was in the order of $0.5/f_{bit}$, where the bit rate f_{bit} was 10 Gbit/s). However, the simulations show that this suboptimal equalizer already yields good results.

Figs. 5 and 6 show the impulse response of the cascade system of SSMF and CFBG before and after equaliza-

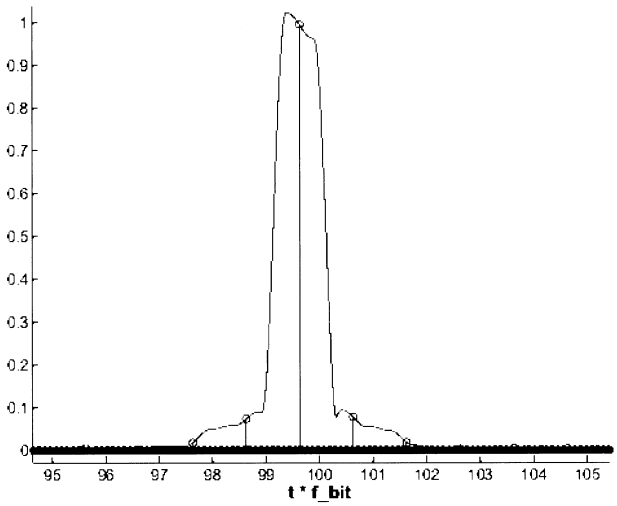


Fig. 5. Impulse Response of the Cascade System (SSMF + CFBG), no Equalization.

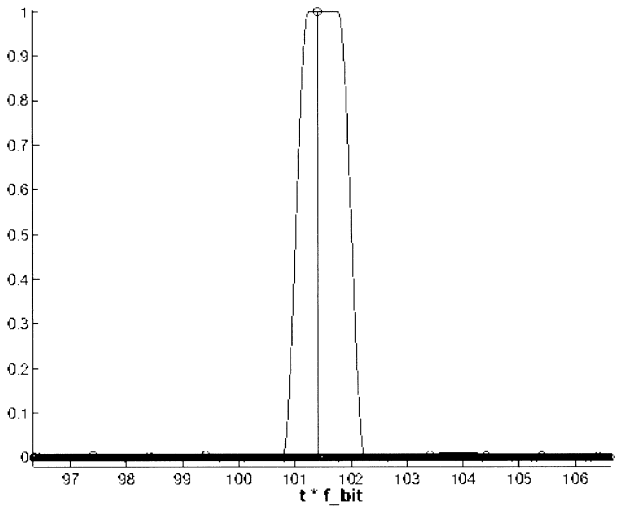


Fig. 6. Impulse Response of the Cascade System (SSMF + CFBG + Equalizer), 9 Coefficients used for the Equalization.

tion (1 span). For the cascade system we assumed a pulse shape of limited bandwidth showing a Cosine edge in the time domain.

Dispersion compensating CFBG realistically show a dispersion in the order of -1400 ps/nm. If after one span a total compensation for the occurring dispersion is desired, a span is therefore correlated with a fiber length in the order of 80 km, as SSMF shows a dispersion of 17 ps/(nm km) in the third window.

In order to quantify the ISI brought in by each impulse response, the regarded impulse response is sampled according to the bit rate f_{bit} and the optimal sample time (in the sense of minimal ISI) is chosen, as shown in Figs. 5 and 6. The optimal samples are normalized to a maximum value of 1 yielding a vector $\boldsymbol{s}$, which is used in order to define an *ISI-penalty (ISIP)* for the regarded impulse response. The $ISIP$-values in dB are defined on the basis of the Euclidean norm $||.||_2$ of $\boldsymbol{s}$:

$$ISIP = 10\log_{10}\left(||\boldsymbol{s}||_2^2\right) \text{ dB}. \tag{9}$$

Without equalization an $ISIP$-value of

$$ISIP_0 = 0.0204 \text{ dB} \tag{10}$$

was calculated, whereas the equalized impulse response lead to an $ISIP$-value of

$$ISIP_{\text{eq}} = 8.5243 \cdot 10^{-4} \text{ dB}. \tag{11}$$

This marks a significant ISI compensation accomplished by the equalization.

In Fig. 7 the improvement achieved by the equalization process is illustrated with the help of eye diagrams. Fig. 7 a) and b) show eye diagrams after a single span, whereas in Fig. 7 c) and d) $M = 3$ spans are regarded (refer to Fig. 4).

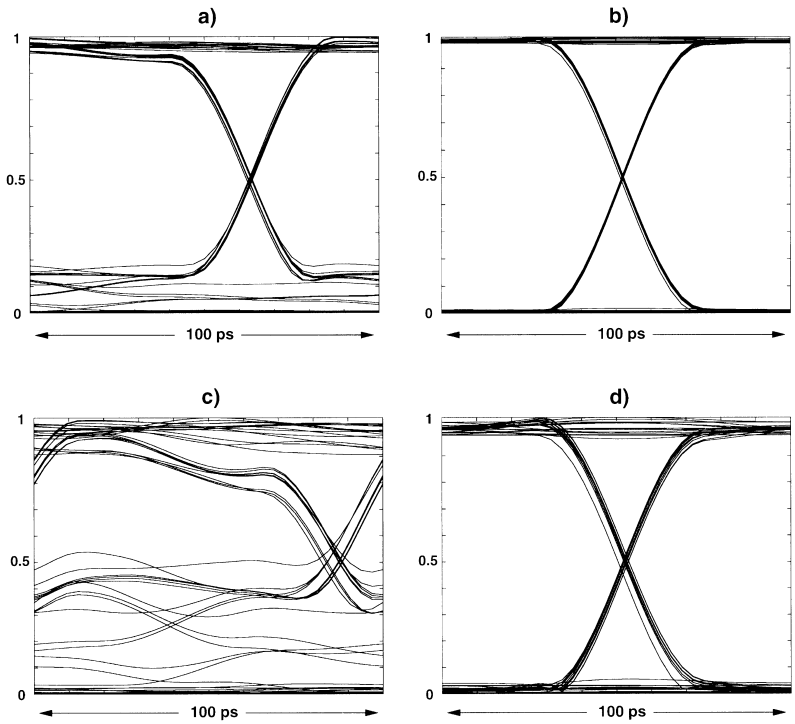


Fig. 7. Cascade System (SSMF + CFBG (+ Equalizer)) a) Eye Diagram after 1 Span (no Equalization) b) Eye Diagram after 1 Span, Equalization with 9 Coefficients c) Eye Diagram after 3 Spans (no Equalization) d) Eye Diagram after 3 Spans, Equalization with 9 Coefficients after each Span.

In Fig. 7 a) and c) no equalizer is employed. Figs. 7 b) and d) show the eye diagrams obtained after an equalization using $n = 9$ coefficients, according to Eqs. (6)–(8), where in the latter case the equalization is done after each span. In the case of Fig. 7 a) the eye diagram already shows a significant degree of degradation, which can lead to a non-tolerable bit error rate, if additional noise is considered. In the case of Fig. 7 c) it is clear that either 3R regeneration or equalization of the received signal is inevitable, even if there is very little additional noise.

5. Conclusion

In Section 2 we presented a model for signal distortions, which appear in optical communication systems when CFBG are used in order to compensate for the chromatic dispersion brought in by an SSMF. The model was derived from group delay measurements within a CFBG.

On the basis of the signal distortion model we presented a closed solution for an optimal equalizer in Section 3. A practical realization of the equalizer in form of a PLC was proposed, as the equalizer turned out to show an FIR structure.

The simulation results of Section 4 showed that the ISI within the cascade system of SSMF and CFBG can significantly be reduced although only a suboptimal equalizer with a rather small number of coefficients was used in the simulations. This has been shown with eye diagrams as well as with values for the corresponding ISI-penalties. It has been shown, that the reduction of ISI is particularly useful in multi-span systems and embodies an alternative approach to 3R regeneration after each span.

Appendix

Abbreviations

3R - Signal regeneration in the electrical domain
BER - Bit error rate
CFBG - Chirped fiber Bragg grating
DCF - Dispersion compensating fiber
FIR - Finite impulse response
FFT - Fast Fourier transform
ISI - Intersymbol interference
ISIP - ISI penalty
PLC - Planar light wave circuit
SSMF - Standard-single-mode fiber
WAN - Wide area network
WDM - Wavelength-division multiplex

References

[1] Fukuchi, K.; Kasamatsu, M. M., et al.: 10.92-Tb/s triple-band/ultra-dense WDM opical-repeatered transmission experiment. Proc. Opt. Fibre. Comm. Conf. OFC2001, Anaheim 2001, postdeadline paper PD24.

[2] Chen, D.; Wheeler, S.; Nguyen, D.; Färbert, A.; Schöpflin, A.; Richter, A.; Weiske, C.-J.; Kotten, K; Krummrich, P. M.; Schex, A.; Glingener, C.: 3.2 Tb/s field trial (80×40 Gb/s) over 3×82 km SSMF using FEC, Raman and tunable dispersion compensation. Proc. Opt. Fibre. Comm. Conf. OFC2001, Anaheim 2001, postdeadline paper PD36.

[3] Haxell, I.; Robinson, N., et al.: 2410 km all-optical network field trial with 10 Gb/s DWDM transmission, Raman and tunable dispersion compensation. Proc. Opt. Fibre. Comm. Conf. OFC2000, Baltimore 2000, postdeadline papers, 290–292

[4] Agrawal, G. P.: Nonlinear Fibre Optics, Academic Press, 1995.

[5] PTDS product information, www.virtualphotonics.com

[6] OptSim product ionformation, www.artis.it

[7] Comsis product information, www.ipsis.com

[8] PHOTOSS product information, www.zkom.de

[9] Elbers, J.-P.; Färbert, A.; Scheerer, C.; Glingener, C.; Fischer, G.: Reduced model to describe SPM-limited fibre transmission in dispersion-managed lightwave systems. IEEE J. Sel. Top. Quant. Electron. **6** (2000), 276–281.

[10] Chraplyvy, A. R.; Tkach, R. W.: What Is The Actual Capacity Of Single-Mode Fibres in Amplified Lightwave Systems. IEEE Photon. Technol. Lett. **5** (1993), 666–668.

[11] Mohs, G.; Stadler, M.; Fürst, C.; Geiger, H.; Fischer, G.: Maximum link length versus data rate for SPM limited systems. Proc. European Conf. Opt. Comm. ECOC 2000, Munich 2000.

[12] Fürst, C.; Mohs, G.; Geiger, H.; Fischer, G.: Performance limits of nonlinear RZ and NRZ coded transmission at 10 Gb/s on different fibres. Proc. Opt. Fibre Comm. Conf. OFC2000, Baltimore 2000, paper WM31.

[13] Färbert, A.; Scheerer, C.; Elbers, J.-P.; .Glingener, C.; Fischer, G.: Novel Optimised Dispersion Management Scheme for Long-Haul Optical Communication Systems. Electron. Lett. (1999).

[14] Hui, R.; Demarest, K. R.; Allen, C. T.: Cross-phase modulation in multispan WDM optical fibre systems. J. Lightw. Techn. **17** (1999), 1018–1026.

[15] Varani, M.; Bellotti, G.; Bononi, A.; Francia, C.: Analysis of cross-phase modulation induced intensity noise in high-speed dispersion compensated transmission systems. Proc. IEEE Lasers and Electro-Opt. Soc. Ann. Meeting LEOS '98. **1** (1998), 376–377.

[16] Fürst, C.; Scheerer, C.; Mohs, G.; Elbers, J.-P.; Glingener, C.: Influence of the dispersion map on limitations due to cross-phase modulation in WDM multispan transmission systems. Proc. Opt. Fibre Comm. Conf. OFC2001, Anaheim 2001, paper MF4.

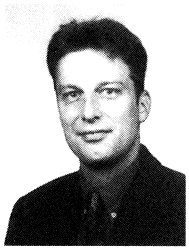
[17] Fürst, C.; Elbers, J.-P.; Scheerer, C.; Glingener, C.: Limitations of dispersion-managed DWDM systems due to cross-phase modulation. Proc. Lasers and Electro-Opt. Soc. 2000 Annual Meeting LEOS 2000, 23–24.

[18] Forghieri, F.; Tkach, R. W.; Chraplyvy, A. R.: Fibre Nonlinearities and Their Impact on Transmission Systems: In Optical Fibre Telecommunications, Vol. IIIa, ed. I. P. Kaminow, T. L. Koch, Academic Press, 1997.

[19] Fürst, C.; Scheerer, C.; Mohs, C.; Geiger H.; Fischer, H.: Comparison of nonlinear crosstalk for RZ and NRZ coding in WDM systems. Proc. European Conf. Opt. Comm. ECOC 2000, Munich 2000.

[20] Chraplyvy, A. R.: Optical Power Limits in Multichannel Wavelength-Division Multiplexed Systems due to Stimulated Raman Scattering. IEE Electron. Lett. **20** (1984), 58–59.

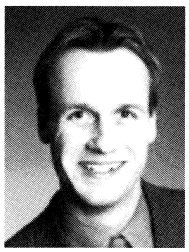
[21] Zirngibl, M.: Analytical model of Raman gain effects in massive wavelength division multiplexed transmission systems. IEE Electron. Lett. **34** (1998), 789–790.
[22] Scheerer, C.; Glingener, C.; Färbert, A.; Elbers, J.-P.; Fischer, G.: SRS crosstalk in preemphasized WDM systems. Proc. Opt. Fibre. Comm. Conf. OFC2000, Baltimore 2000, vol. **2**, 293–295.
[23] Forghieri, F.; Prucnal, P. R.; Tkach, R. W.; Chraplyvy, A. R.: RZ versus NRZ in nonlinear WDM systems. IEEE Photon. Techn. Lett. **9** (1997), 1035–1037.
[24] Smith, R. G.: Optical Power Handling Capacity of Low Loss Optical Fibres as Determined by Stimulated Raman and Brillouin Scattering. Appl. Opt. **11** (1972), 2489–2494.
[25] Cotter, D.: Supression of Stimulated Brioullin Scattering During Transmission of High-Power Narrowband Laser Light in Monomode Fibre, IEE Electron. Lett. **18** (1982), 638.



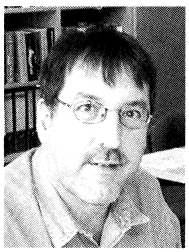
Christoph Glingener was born in Arnsberg, Germany, in 1968. He received his diploma and PhD in electrical engineering from Dortmund University, in 1993 and 1998 respectively. In 1998, he joined the Advanced Technology Department of Siemens AG, Information and Communication Systems – Optical Networks, in Munich and is presently Vice President and Head of the Department. Dr. Glingener authored and co-authored more than 60 scientific publications and is member of the OSA.

Jan Mietzner was born in Rendsburg, Germany in 1975. He received the Dipl.-Ing. degree from the Faculty of Engineering, University of Kiel, Germany in 2001. Since 2001, he is a Ph.D. student at the Information and Coding Theory Lab, University of Kiel. He is currently working in the area of future wireless communication systems. His research interests are physical layer aspects as channel coding and space-time codes.

Sven Otte was born in Husum, Germany, in 1971. He received the diploma degree in electrical engineering from the University in Kiel, Germany in 1996. Since 1997 he is working toward his Ph.D. degree in electrical engineering at the chair for communications at the University of Kiel. His research interests include modelling of opical communication systems and electronic equalization of the optical channel in high speed transmission systems.



Marc Bohn was born in Wedel, Germany 1973. He received the diploma degree (Dipl.-Ing.) in 1999 from the University of Kiel, Germany. From 2000 he is a research assistant at the Institut für Nachrichtentechnik of the University of Kiel. Currently he is working on optical filter applications to enhance the performance of high bitrate optical transmission systems.



Werner Rosenkranz studied Electrical Engineering at the University of Erlangen-Nürnberg, Erlangen, Germany. There he received the Ph.D. and the Habilitation at the Lehrstuhl fr Nachrichtentechnik. Since 1989 he worked with Philips Kommunikations Industrie, later Lucent Technologies, in Nürnberg, Germany, on transmission-aspects in digital communication systems with focus on synchronization, optical and digital TV-transmission, and simulation. Since 1997 he is professor and head of the chair for communications at the faculty of engineering of the University of Kiel, Kiel, Germany. His research interests are communication systems, currently including high-speed optical systems and networks, measurement and simulation techniques as well as synchronization problems in digital communications.