Optimization of 40 Gb/s WDM Systems Using Super-Gaussian RZ Pulses

Jong–Hyung Lee*, Dae–Hyun Han, and Yong–Jae Lee

Department of Electronic Engineering, Dongeui University, Busan, 614-714, Korea

Byeong–Yoon Choi

Department of Computer Engineering, Dongeui University, Busan, 614-714, Korea

40 Gbps WDM Systems using super-Gaussian RZ pulses have been studied by numerical simulation to optimize their performance. The assumption of standard single mode fiber is valid when existing WDM systems are required to upgrade their performance to 40Gbps. It is shown that the standard single mode fiber can transmit optical signals over 720 km (Q > 10) by optimizing optical and electrical filter characteristics at the receiver and by compensation of dispersion. However, it is also shown that ±0.3% dispersion compensation tolerance per span (80 km) could prohibit transmitting over 320km (Q > 10). In addition, a duty cycle of less than 0.4 degrades system performance significantly.

Keywords : RZ format, Standard Single Mode Fiber, WDM, 40Gb/s

OCIS codes : (060.0060) Fiber optics and optical communications; (060.2330) Fiber optics communications; (060.4510) Optical communications

I. INTRODUCTION

As the demand for bandwidth is ever increasing, we often need to decide how to upgrade the transmission capacity in installed WDM systems. One of the easiest ways is to increase bit rate of each channel, which requires no replacement of the installed fibers. However, most installed fiber, which is the standard single mode fiber (SSMF), has large chromatic dispersion, typically 16 ps/nm/km at 1550 nm window. Therefore, the system performance using SSMF can be degraded significantly at a higher bit rate if cautious design methodology does not apply[1-3].

In this paper, we investigate by numerical simulations the optimum performance of 40 Gbps WDM systems using the standard single mode fiber. In section II, the receiver performance is optimized first without fibers using RZ format with a duty cycle of 0.5. In section III, transmission performance is investigated using the optimum receiver in section II. Chromatic dispersion is assumed to be compensated 100% by the commercially

available dispersion compensation fiber, DCF. Section IV shows the simulation results with decreased RZ duty cycles to find the possible improvements, and simulation results including residual dispersion and transmitter chirp are discussed in section V. Conclusions follow in section VI.

II. OPTIMIZATION OF THE RECEIVER PERFORMANCE

To achieve maximum Q-values[4,5], we first consider a 40 Gb/s WDM system using RZ format without fibers to optimize the optical and electrical receiver bandwidths. Figure 1 shows the spectrum and the eye diagram (channel @ 193.41 THz) of the RZ transmitter with a duty cycle of 0.5, which was used to evaluate 40 Gb/s WDM transmission over dispersion compensated standard SMF. To reduce simulation time, only a 5 channel WDM signal was investigated, with the center channel @ 193.41 THz chosen to obtain an estimate of system performance.

The bandwidths of the optical filters and the electrical filters were varied independently in the range of 30…110

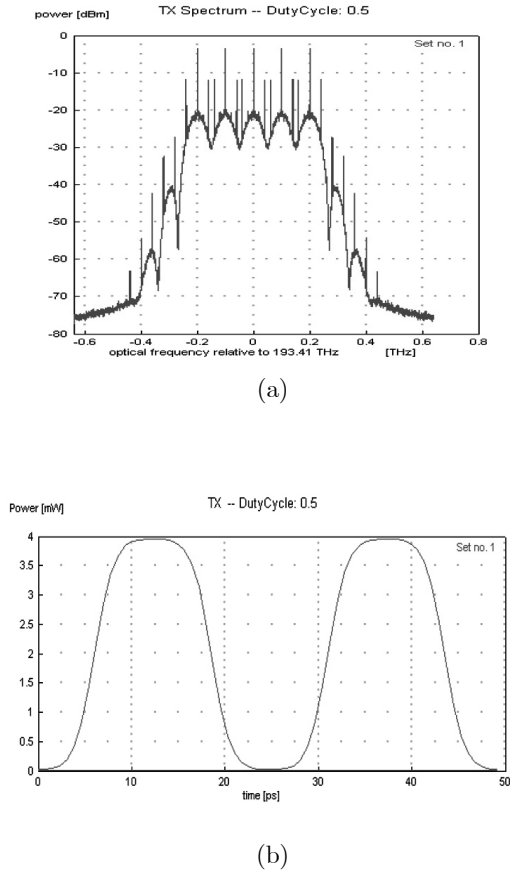*Corresponding author: jonghlee@deu.ac.kr

(a)

(b)

FIG. 1. Spectrum (a) and eye diagram (b) of the 40 Gb/s RZ Transmitter with a duty cycle of 0.5

(a)

(b)

FIG. 2. Q-values vs. optical filter bandwidth (a) Gaussian filter (b) Sinc-shaped filter

GHz and 20···70 GHz, respectively. To emulate a realistic scenario regarding the noise disturbances at the receiver, the noise source was included right after the transmitter to give an optical signal-to-noise ratio $OSNR_{TX} = 20$ dB (in a measurement bandwidth of 100 GHz). Figure 2 shows the results for a Sinc-shaped and a Gaussian-shaped optical receiver filter [6]. In both cases, the electrical receiver filter as a post-detection filter was a 5th order Bessel low-pass. In the figure solid lines show the Q-values using the optimum bandwidth of the post-detection filter. We could obtain a larger optimum Q-value with the Gaussian optical filter. Because the Gaussian-shaped optical filter performs better than the Sinc-shaped filter, a 101 GHz Gaussian optical filter and a 5th order Bessel filter with a cutoff frequency of 53 GHz, which are optimum, were used for all simulations with a duty cycle of 0.5.

III. TRANSMISSION RESULTS WITH A RZ DUTY CYCLE OF 0.5

In this section, we investigate the transmission effects of the 5 channel WDM system with the optimum receiver bandwidths found in section II. Figure 3 shows the repeated transmission path for the performance evaluation of 40
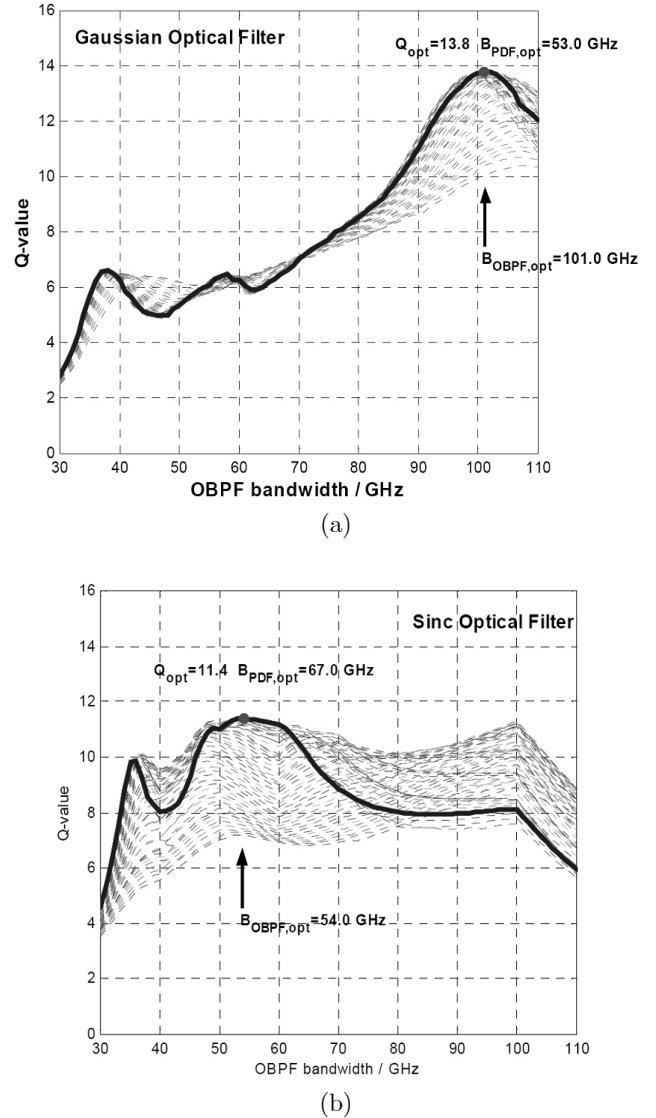
Gb/s RZ transmission. EDFA is assumed to have flat gain characteristics with 6 dB noise figure and the fiber parameters used in simulation are included in Table 1. One span consists of 80 km SSMF, DCF, and two EDFAs to compensate fiber losses. The chromatic dispersion is post-compensated by DCF, and the input power into the SSMF(-4.0 ... +6.0 dBm) and into the DCF(-6.0 ··· +4.0 dBm) were varied. For the central channel at 193.41 THz, the Q-value was monitored after each span. The transmission distance after each loop is considered as the length of SSMF, which is set to 80 km. A chirp free transmitter signal and a compensation ratio of 100% were assumed.

Figure 4 shows the calculated Q-values vs. SSMF input power per channel for different transmission distances in simulations. For each Q-value, the optimum launch power per channel into the DCF is shown (small numbers

TABLE 1. Fiber Parameters

	Attenuation [dB/km]	Chromatic Dispersion [ps/nm/km]	Dispersion Slope [ps/nm^2/km]	Effective Core Area [μm^2]	Nonlinear Refractive Index [m^2/W]
SSMF	0.23	16	0.08	80	2.6×10^{-20}
DCF	0.5	-90	-0.08×90/16	50	2.6×10^{-20}

FIG. 3. Repeated transmission path

FIG. 4. Q-values vs. SSMF launch power per channel after different transmission distances.

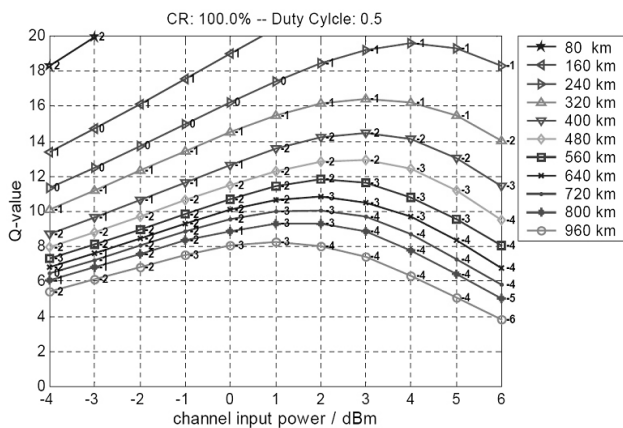
FIG. 5. Q-values vs. launch powers per channel after 9 spans.

next to the symbols, in dBm). As can be seen in Figure 4, transmission distances of up to 720 km (9 spans) can be bridged for Q $\geq$ 10. In this case, the optimum launch power per channel for the SSMF and the DCF are 2 dBm and −3 dBm, respectively. The corresponding contour plot is shown in Figure 5. Figure 5 indicates the sensitivity of the maximum Q value in terms of launch power per channel for the SSMF and the DCF.

IV. RZ TRANSMISSION FOR DECEASED RZ DUTY CYCLES

1. Optimization of the receiver performance

To improve system performance, we analyzed the aforementioned 5-channel RZ-system with modified duty cycles (0.4 and 0.3) of the transmitted RZ waveform[7]. Again, initially the receiver filters were optimized with respect to the particular duty cycle. Since the central channel is supposed to be most affected by its neighbors, only this channel was analyzed as before. Additionally, only the Gaussian optical receiver filter was considered, since it always performs better than its Sinc-shaped
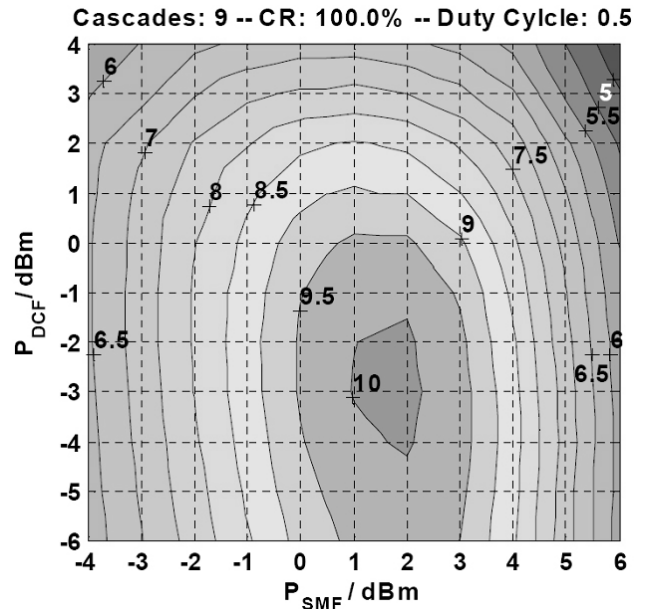
counterpart in section II.

For the investigated duty cycles of 0.4 and 0.3, Figure 6 shows the resultant Q-values vs. the optical and electrical receiver bandwidths. The optimum Q value for a duty cycles of 0.4 was obtained with a Gaussian-shaped optical filter ($B_{OBPF,opt}$ = 89 GHz) and a 5th order electrical Bessel low-pass filter ($B_{PDF, opt}$ = 37 GHz) in the receiver.

On the other hand, for a duty cycle of 0.3 we observed a severe breakdown of the system performance (Q_{opt} = 6.8). This results from an excessive spectral broadening, which is inherently associated with the decrease of the duty cycle. As a result, in this case the system performance is supposed to be limited mainly by inter-channel crosstalk rather than by noise or by signal distortions due to SPM-GVD interactions.

Thus, simulations with Super-Gaussian pulses for duty cycles smaller than 0.4 are not promising and consequently are not considered further.

2. Results of RZ transmission with a RZ duty cycle of 0.4

The results of the system simulations for the postcompensated systems are depicted in Figure 7 and Figure 8. A chirp free transmitter signal with a RZ duty cycle
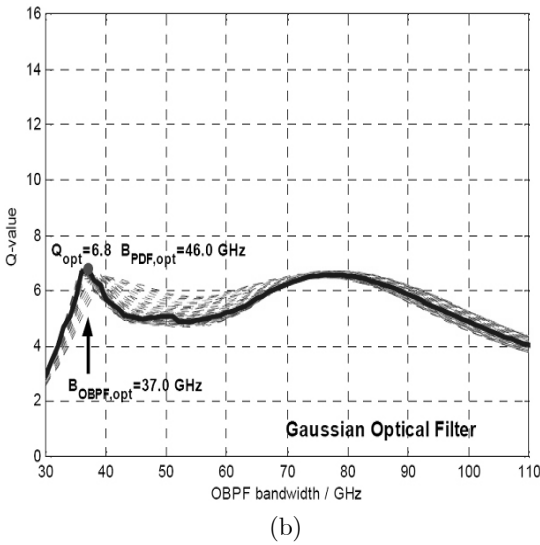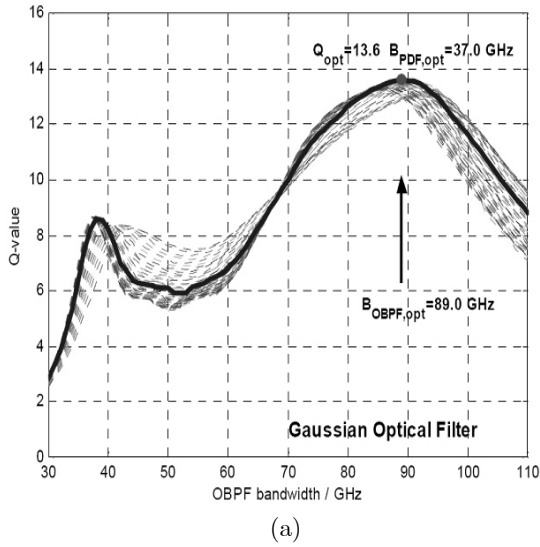
(a)

(b)

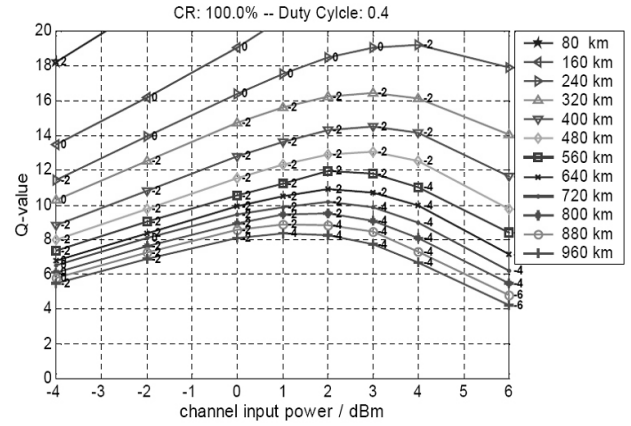FIG. 6. Q-values vs. optical filter bandwidth (a) duty cycle = 0.4 (b) duty cycle = 0.3

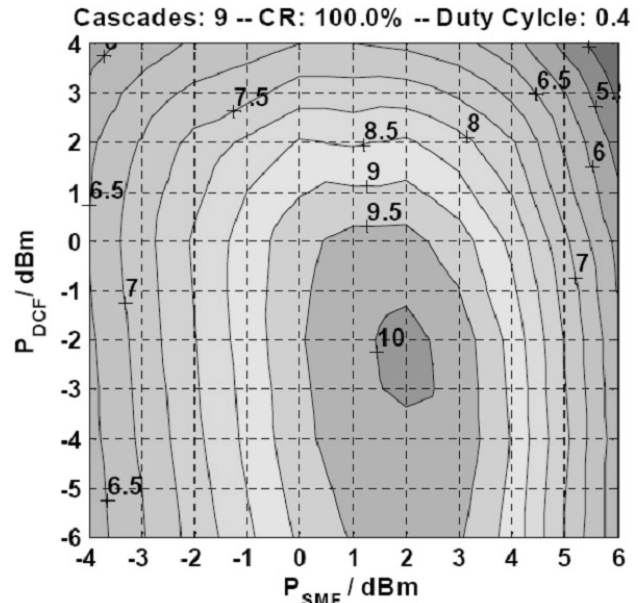FIG. 7. Q-values vs. SSMF launch power per channel after different transmission distances with a duty cycle of 0.4.

FIG. 8. Q-values vs. launch powers per channel after 9 spans with a duty cycle of 0.4.

of 0.4 and a compensation ratio of chromatic dispersion = 100% were assumed. As in the previous simulations, the input powers into the SSMF ($-4.0 \cdots +6.0$ dBm) and into the DCF ($-6.0 \cdots +4.0$ dBm) were varied independently to identify the optimum operating condition.

With the post-compensation of chromatic dispersion, distances of up to 720 km (9 spans) can be bridged for $Q \geq 10$ (Figure 7). The optimum input powers into the SSMF and the DCF are about 2 dBm and -2 dBm, respectively. The corresponding contour plot is shown in Figure 8. Compared to the results obtained for a RZ duty cycle of 0.5 (Figure 4 and Figure 5), no significant change (actually a slight increase of the Q-values) can be observed for the RZ transmission with a duty cycle of 0.4.

It's worth noting that the observed similarity of the results for RZ duty cycles 0.5 and 0.4 is only found with

the individually optimized receiver filters. Practically, that means even a slight change in the transmitted pulse shape requires an adjustment of the respective receiver filters.

V. EFFECTS OF RESIDUAL CHROMATIC DISPERSION AND TRANSMITTER CHIRP

Since the dispersion parameter D is wavelength-dependent, 100% compensation may not be achievable due to the dispersion slope mismatch between SSMF and DCF if the same DCF must compensate dispersion over the entire bandwidth of a WDM system. To study the effects of residual dispersion, the dispersion value
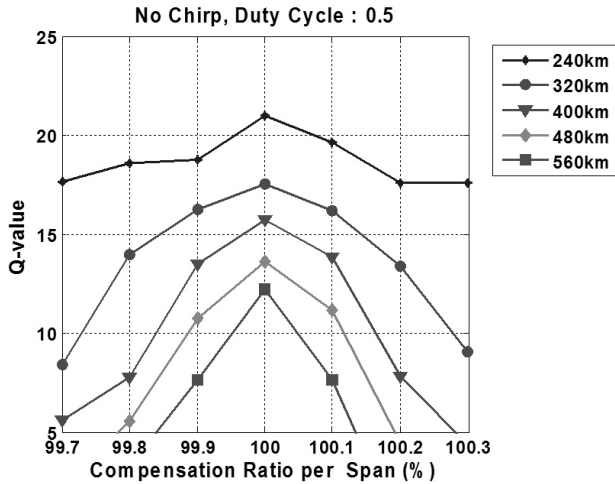
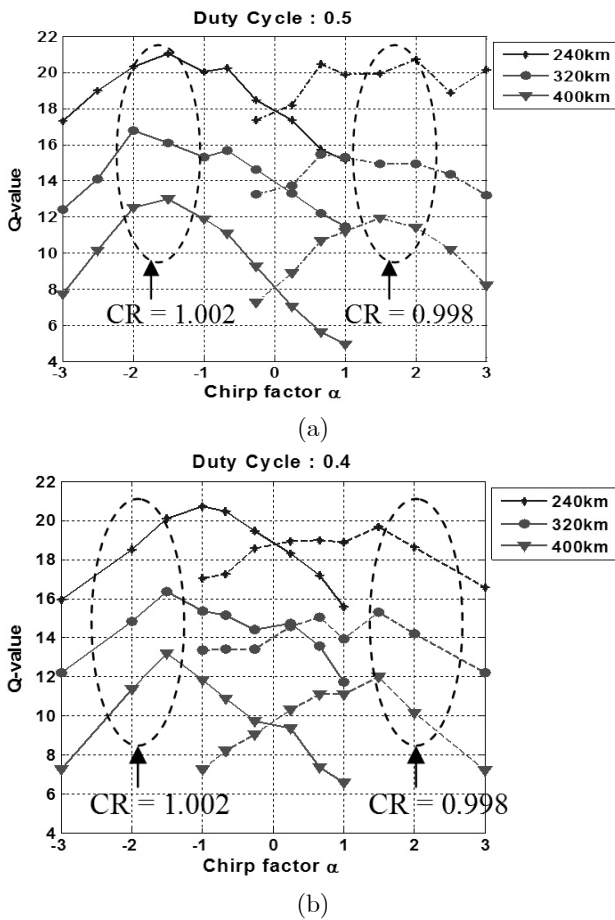FIG. 9. Q-values vs. compensation ratio per span.

(a)

(b)

FIG. 10. Effects of transmitter chirp factor (a) duty cycle = 0.5 (b) duty cycle = 0.4

of DCF has been varied slightly from 99.7% (under-compensated) to 100.3% (over-compensated). All other simulation parameters were the same as in section III with the optimized signal power levels. While transmission distance is increased, the accumulated residual dispersion is indeed more detrimental to the system performance as observed in Fig. 9. Unless a dispersion slope compensator is employed, ±0.3% dispersion compensation tolerance per span could prohibit transmitting over 320 km (Q > 10).

To verify the possibly positive influence of modulator chirp combined with residual dispersion on system performance, the chirp of the Mach-Zehnder modulator (MZM) in simulations was varied. The chirp behavior of the MZM is typically characterized by the chirp factor α [8-10]. While the effect of the modulator chirp is not noticeable with 100% compensation ratio, Fig. 10 suggests that we could obtain significant improvements in system performance by controlling the chirp in the presence of residual dispersion even though careful selection of chirp sign is required for each channel.

VI. CONCLUSION

In this paper, we studied 40 Gbps WDM systems numerically to find optimum parameters. It is assumed that optical fiber is standard single mode fiber, which is most widely installed in the world, and the transmitter pulse is super-Gaussian RZ.

We optimized the bandwidth of the filters at the receiver(optical and electrical), and showed that Gaussian-shaped optical filter in the receiver can have better performance compared to Sinc-shaped filter. We also showed that the duty cycle of less than 0.4 in the transmitter pulse will degrade system performance due to its wider spectrum. In addition, by optimizing input power levels to SSMF and DCF, we showed that we may achieve that over 720km (Q > 10) transmission distance if dispersion is 100% compensated. The effect of residual dispersion and transmitter chirp is also investigated. In 40 Gb/s systems using installed fibers, PMD, which is not included in this study, could be a critical system impairment. It is known that RZ performs better than NRZ in the presence of PMD and a smaller duty cycle is more resistent to PMD [11,12]. However, the effect of broader spectra due to shorter pulses on dispersion and inter-channel interferences is not clear yet. By designing system with a higher margin, we may avoid system failure due to PMD effects. For optimum system design we need to further investigate PMD effects including the impact of duty cycle, which will be one of the future topics.

REFERENCES

[1] H. Taga, "Long distance transmission experiments using WDM technology," *J. Lightwave. Tech.,* vol. 14, no. 6, pp. 1287-1298, June 1996.

[2] D. Breuer, K. Obermann, K. Petermann, "Comparison of N × 40 Gb/s and 4 N × 10 Gb/s WDM Transmission over standard single-mode fiber at 1.55 μm," *IEEE Photon. Technol. Lett.,* vol. 10, no. 12, pp. 1793-1795, Dec. 1998.

[3] F. Forghieri, "Granularity in WDM Networks: The Role of Fiber Nonlinearities," *IEEE Photon. Technol. Lett.,* vol. 8, no. 10, pp. 1400-1402, Oct. 1996.

[4] C.J. Anderson, J.A. Lyle, "Technique for evaluating system performance using Q in numerical simulations exhibiting intersymbol interference," *Electronics Letters,* vol. 30, no. 1, pp. 71-72, Jan. 1994.

[5] G.P. Agrawal, *Lightwave Technology Telecommunication Systems* (John Wiley & Sons, New Jersey, 2005) Chapter 5.

[6] C. K. Madsen and J. H. Zhao, *Optical Filter Design and Analysis,* (John Wiley & Sons, New York, 1999) Chapter 4.

[7] M.I. Hayee, A.E. Willner, "NRZ Versus RZ in 10-40 Gb/s Dispersion-Managed WDM Transmission Systems," *IEEE Photon. Technol. Lett.,* vol. 11, no. 8, pp. 991-993, 1999.

[8] G. Wenke, M. Kimmek, "Considerations on the α-factor of Nonideal, External Optical Mach-Zehnder Modulators," *J. Opt. Comm.,* vol. 17, no. 2, p. 42-48, 1996.

[9] F. Koyama, K. Iga, "Frequency Chirping in external Modulators," *J. Lightwave. Tech.,* vol. 6, no. 1, pp. 87-93, Jan. 1988.

[10] A. H. Gnauck, R.W. Tkach, M. Mazurczyk, "Interplay of Chirp and Self Phase Modulation in Dispersion-Limited Optical Transmission Systems," Proceedings of European Conference on Optical Communications, TuC4.4, pp. 105-108, 1993.

[11] H. Sunnerud, M. Karlsson, and P. A. Andrekson, "Analytical theory for PMD-compensation," *IEEE Photon. Technol. Lett.,* vol. 12, pp. 50-52, Jan. 2000.

[12] H. Sunnerud, M. Karlsson, and P. A. Andrekson, "A comparison between NRZ and RZ Data Formats with respect to PMD-Induced System Degradation," *IEEE Photon. Technol. Lett.,* vol. 13, no. 5, pp. 448- 450, May 2001.