Available online at www.sciencedirect.com
ScienceDirect
Optics Communications 281 (2008) 3495–3500
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Analysis and simulation of the effect of spectral width over intensity noise under the impact of higher-order dispersion parameters in the optical communication systems

Vishal Sharma [a,*], Amarpal Singh [b], Ajay K. Sharma [c]

[a] College of Engineering and Management, Goindwal Road, Bhawanipur, Kapurthala, Punjab, India
[b] Beant College of Engineering and Technology, Gurdaspur, Punjab, India
[c] NIT, Jallandhar, Punjab, India

Received 11 October 2007; received in revised form 29 December 2007; accepted 25 February 2008

Abstract

In this paper, we analyzed the effect of spectral width of different light sources under the individual and combined impact of first- and second-order dispersion parameters both analytically and graphically. This work also covers the amount of intensity noise introduced in an optical system and the power penalty required to compensate this intensity noise at different optical distances. It has been also investigated that reducing the spectral width can minimize the intensity noise and the power penalty under the individual and the combine impact of higher- order dispersion parameters. An experimental set up is also analyzed to support our results.

Keywords: Intensity noise; Power penalty; Higher-order dispersion; Spectral width

1. Introduction

An important limitation to the bit rate-distance product achievable in a fiber-optic broadband communication link arises because of the group-velocity dispersion (GVD) in fiber. In optical communication systems, using standard dispersion fiber at wavelength of 1.5 μm, the transmission distance is limited by fiber chromatic dispersion rather by the fiber loss. An expansion to the higher-order terms of the propagation constant is essential in order to design and develop an efficient high-bit rate broadband optical communication system or network. Higher-order dispersion terms are the forces destructive of pulse propagation in ultra high-bit rate optical transmission systems.

It is investigated that the degradation of an optical system performance is mainly due to the intensity noise from a semiconductor local oscillator laser. A statistical model for the optical receiver has already presented to calculate the bit error rate and the power penalty resulting from the local oscillator intensity noise. The power penalty depends critically on the noise power, data rate, and spectral characteristics of the noise. The system penalty due to this noise in the intensity modulation and direct detection optical transmission using an external modulator increases as the optical distance increases and can be reduced by decreasing the spectral width of the light source.

Wang et al. [1] investigates the impact of dispersion terms on optical fiber communication systems using small signal analysis. Crognale et al. [2] extended the analysis of the Wang by comparing the effect of second- and third-order dispersion term. Peral et al. [3] derived an expression for the large signal theory for the propagation of an optical wave with sinusoidal amplitude and the frequency modulation in the dispersive medium. Peterman

* Corresponding author. Tel.: +91 9855553322/1832 571393; fax: +91 1822 265171.
E-mail address: er_vishusharma@yahoo.com (V. Sharma).

0030-4018/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2008.02.056

et al. [4] discussed the FM–AM conversion for a dispersive optical fiber with respect to binary intensity modulated PCM systems. This work is also limited to the first-order dispersion parameter. Further, the work reported in [1,2] was extended in [5,6] by presenting an improved analysis for analyzing the influence of the higher-order dispersion on dispersive optical communication system. Moreover, this theory is applicable to evaluate the impact of higher-order dispersion on the small signal frequency response and RIN of an ultra-fast laser diode similarly as mentioned in [2]. The intensity noise, power penalty analysis with respect to spectral width of laser was not reported in earlier work [1–11] for higher-order dispersion terms. Cartaxo et al. [12–15] presented an improved rigorous small signal theory for linear and dispersive single-mode fibers operating near zero-dispersion wavelength to derive small signal IM and FM fiber transfer functions, intensity and frequency noise spectra after transmission under the impact of first-order fiber dispersion only and with line width enhancement factor of 5. But the intensity noise and power penalty analysis at different spectral widths including first- and second-order dispersion terms was not reported in earlier work [1–15].

In this paper, we discussed the effect of spectral width of laser over power penalty and intensity noise introduced in the optical system under the individual and combined effect of first- and second-order dispersion parameters in optical distance range of 1000–10,000 km. Also this paper pointed out that as we increase the optical distance, the impact of second-order dispersion parameter becomes more effective and hence, more power is required to compensate it. The effect of spectral width of light source including effect of second- and third-order dispersion parameters has been discussed analytically and briefly in the Section 1 and shown graphically in Section 2. In this paper, we also analyzed an experimental setup to support our results in section 3.

2. Section I: Theory

Let us consider a single-mode fiber transmission line and assume that the input field at the fiber input can be given by [9] as

$$E(t) = E_{\text{in}}(t) \cdot e^{i\omega t} \tag{1}$$

The input field can be transferred to the output field in the terms of propagation constant, β as

$$E_{\text{o}}(\omega) = E_{\text{in}}(\omega) \cdot e^{-i\beta L} \tag{2}$$

where β can be expanded as

$$\beta = \beta_{\text{o}} + (\omega - \omega_{\text{o}})\tau + \frac{1}{2}(\omega - \omega_{\text{o}})^2 \frac{d\tau}{d\omega} + \frac{1}{6}(\omega - \omega_{\text{o}})^3 \frac{d^2\tau}{d\omega^2} + \ldots \tag{3}$$

Here

$$\beta_2 = \text{First-order dispersion} = -\frac{\lambda^2}{2\pi c}\frac{\partial\tau}{\partial\lambda} \tag{4}$$

$$\beta_3 = \text{Second-order dispersion} = -\frac{\lambda^2}{(2\pi c)}\left[\lambda^2 \frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right] \tag{5}$$

As reported in [6], we neglect the phase and group delay i.e. $\beta_{\text{o}}L$ and $\frac{d\tau}{d\omega}$ because both terms produce only phase delay of the carrier signal and have no influence on the distortion on the signal and the dispersion parameters are defined as

$$F_2 = -\frac{L}{2}\frac{d\tau}{d\omega} = \frac{L}{2}\frac{\lambda^2}{(2\pi c)}\frac{\partial\tau}{\partial\lambda} \tag{6}$$

$$F_3 = \frac{L}{6}\frac{d^2\tau}{d\omega^2} = \frac{L}{2}\frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2\frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right] \tag{7}$$

The intensity of noise level under the individual and the combine effect of first- and second-order dispersion parameters as reported in [5,6] can be calculated as

$$r_{F_2F_3} = \frac{32}{3}F_2^2\pi^3\Delta v B^3 + \frac{144}{3}F_3^2\pi^4\Delta v^2 B^2 - \frac{192}{3}F_2F_3\pi^4\Delta v^2 B^2 \tag{8}$$

$$r_{F_2} = \frac{32}{3}F_2^2\pi^3\Delta v B^3 \tag{9}$$

$$r_{F_3} = \frac{144}{3}F_3^2\pi^4\delta v^2 B^4 \tag{10}$$

The power penalty can be calculated given by [7] as

$$\delta pp = -5\log_{10}\left[\frac{P(r_1)}{P(0)}\right] \tag{11}$$

where

$$P(0) = \frac{Q\cdot\sigma\cdot t + Q^2\cdot q\cdot\Delta f}{R} = \text{Power sensitivity at } r_i = 0$$

$$P(r_i) = \text{Power sensitivity with } r_i = \frac{Q\cdot\sigma\cdot t + Q^2\cdot q\cdot\Delta f}{R\cdot(1 - r_i^2\cdot Q^2)}$$

R = Responsivity ranges from 0.4 to 0.95,
Q = Ratio of signal current to noise current that measure the BER.

3. Section II: Results and discussion

Referring to ITU-T Rec. 653 recommendation [8], we assume $\lambda_{\text{o}} = 1550$ nm, and $\frac{\partial^2\tau}{\partial\lambda^2} = 0.085$ ps/nm^2-km. Also, the dispersion parameters are given as

- $F_2 = 12.75 \times 10^{-24}$ L/km
- $F_3 = 2.955 \times 10^{-38}$ L/km
- $Q = 6$, $B = 10$ GHz, $\Delta v = 10$ MHz
- $r_{F_2F_3}$ = Intensity noise with $F_2 + F_3 = 5.38 \times 10^{-3}$
- r_{F_2} = Intensity noise with F_2 only $= 5.38 \times 10^{-3}$
- r_{F_3} = Intensity noise with F_3 only $= 4.08 \times 10^{-14}$

In the range of optical distance from 100 to 10,000 km, we observed that the intensity noise increases with the optical length under the individual and the combined effect of

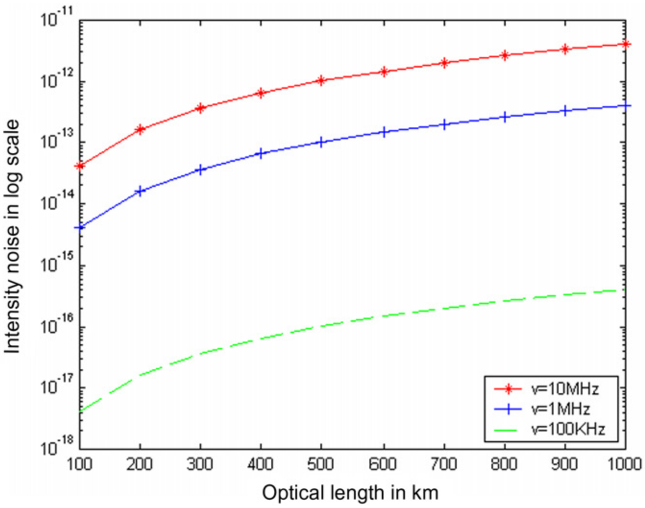

Fig. 1. Intensity noise versus optical length up to 1000 km at different value of Spectral line width under the effect of F_3 only.

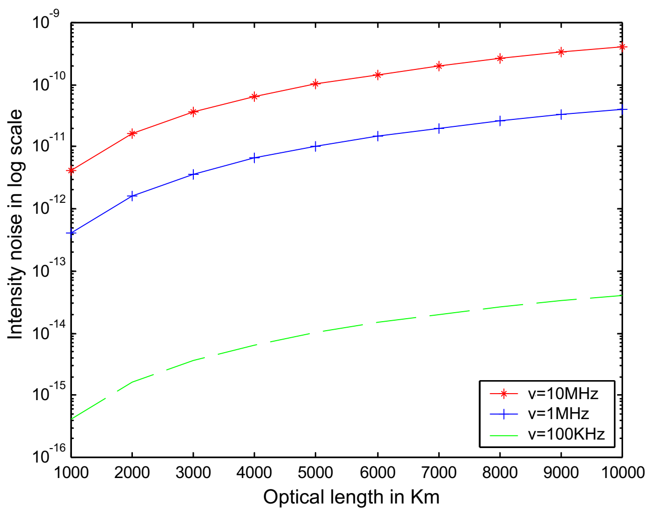

Fig. 2. Intensity noise versus optical length up to 10,000 km at different value of spectral line width under the effect of F_3 only.

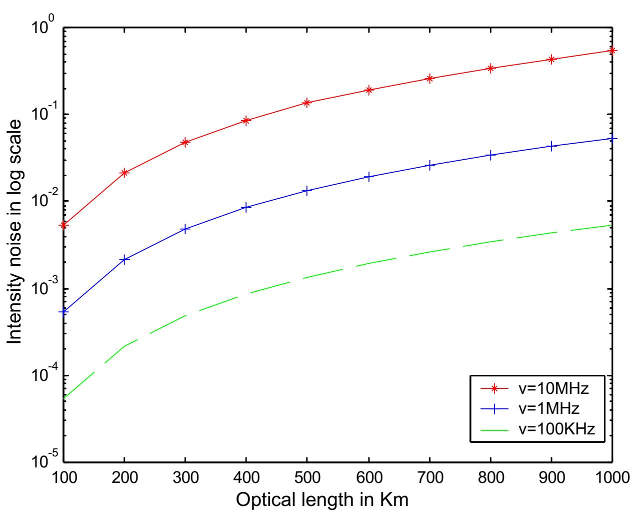

Fig. 3. Intensity noise versus optical length up to 1000 km at different value of Spectral line width under the combined effect of F_2 and F_3.

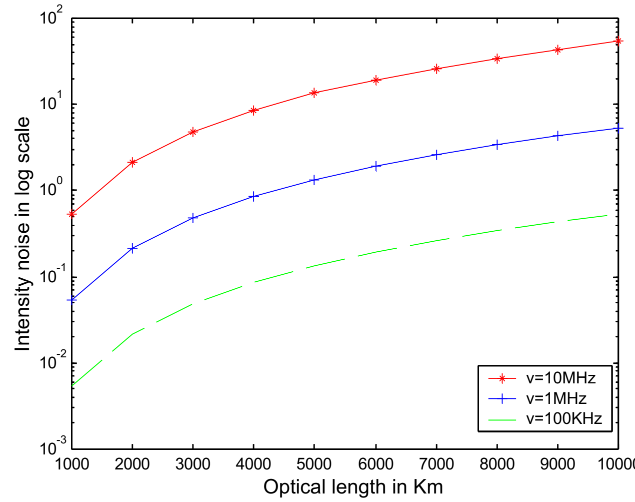

Fig. 4. Intensity noise versus optical length up to 10,000 km at different value of spectral line width under the combined effect of $F_2 + F_3$.

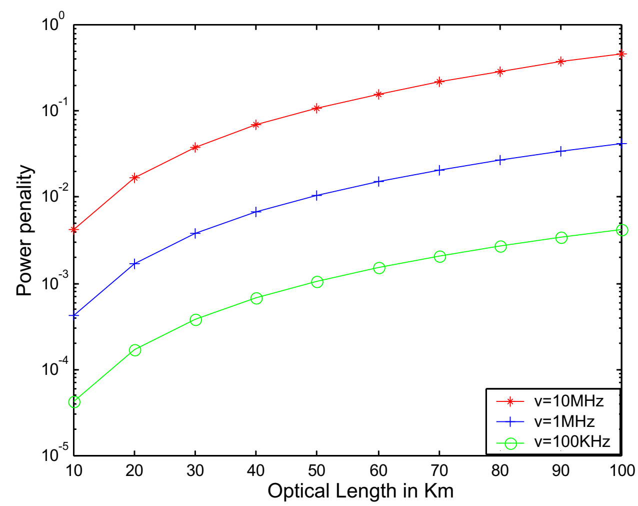

Fig. 5. Power penalty versus optical length up to 100 km at different value of spectral line width under individual effect of F_2.

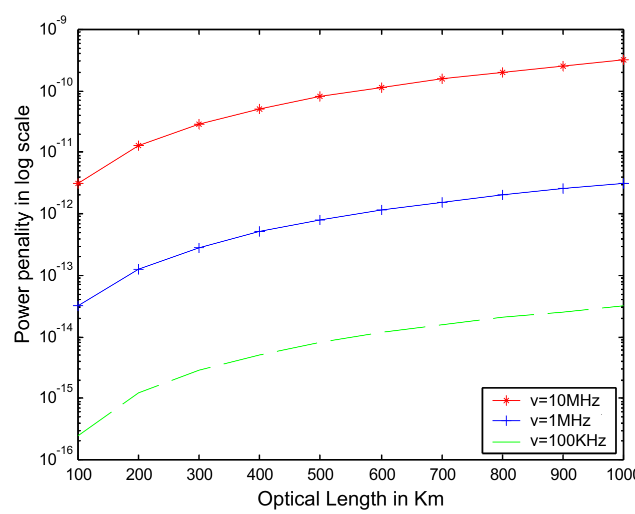

Fig. 6. Power penalty versus optical length up to 100 km at different value of spectral line width under the individual effect of F_3.

first- and second-order dispersion ($F2 + F3$) parameters at spectral width varies from 10 MHz to 100 kHz as shown in Figs. 1–4 Under the individual effect of $F3$, the intensity noise is very small and increases at a very small rate with optical distance up to 1000 km that can be seen from the Fig. 1. But Fig. 2 reveals that the intensity noise increases comparatively at a high rate as the optical distance increases up to 10,000 km. Also under the combined effect of first- and second-order dispersion ($F2 + F3$) parameters, the intensity noise increases to a very large amount as illustrated by Figs. 3 and 4. From Figs. 1–4, it is also observed that as we reduce the spectral width to the kHz range, the intensity noise reduces which further reduces the power required to compensate this noise.

Further, we calculate the amount of power penalty required to compensate the loss introduced in the system

Table 1
Fiber parameters

Optical length	100 km
Reference frequency	193.04992 THz
Loss	0.25 dB/km
Non linear refractive index	3.0e−20 m^2/W
Effective core area	67.43e−6 m^2
Fiber non linearity coefficient	1.8 W/km

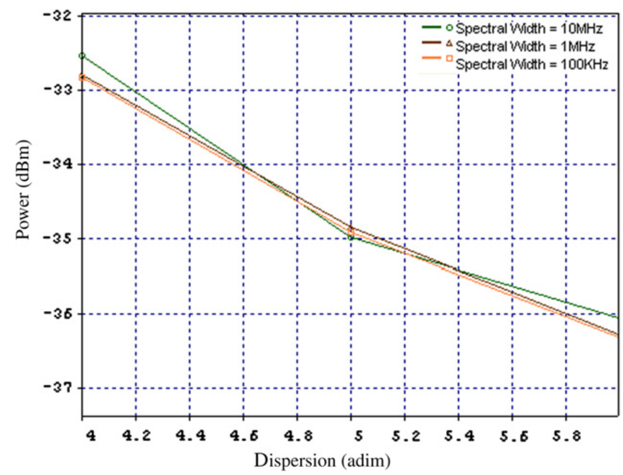

Fig. 7. Channel power versus dispersion at different spectral width.

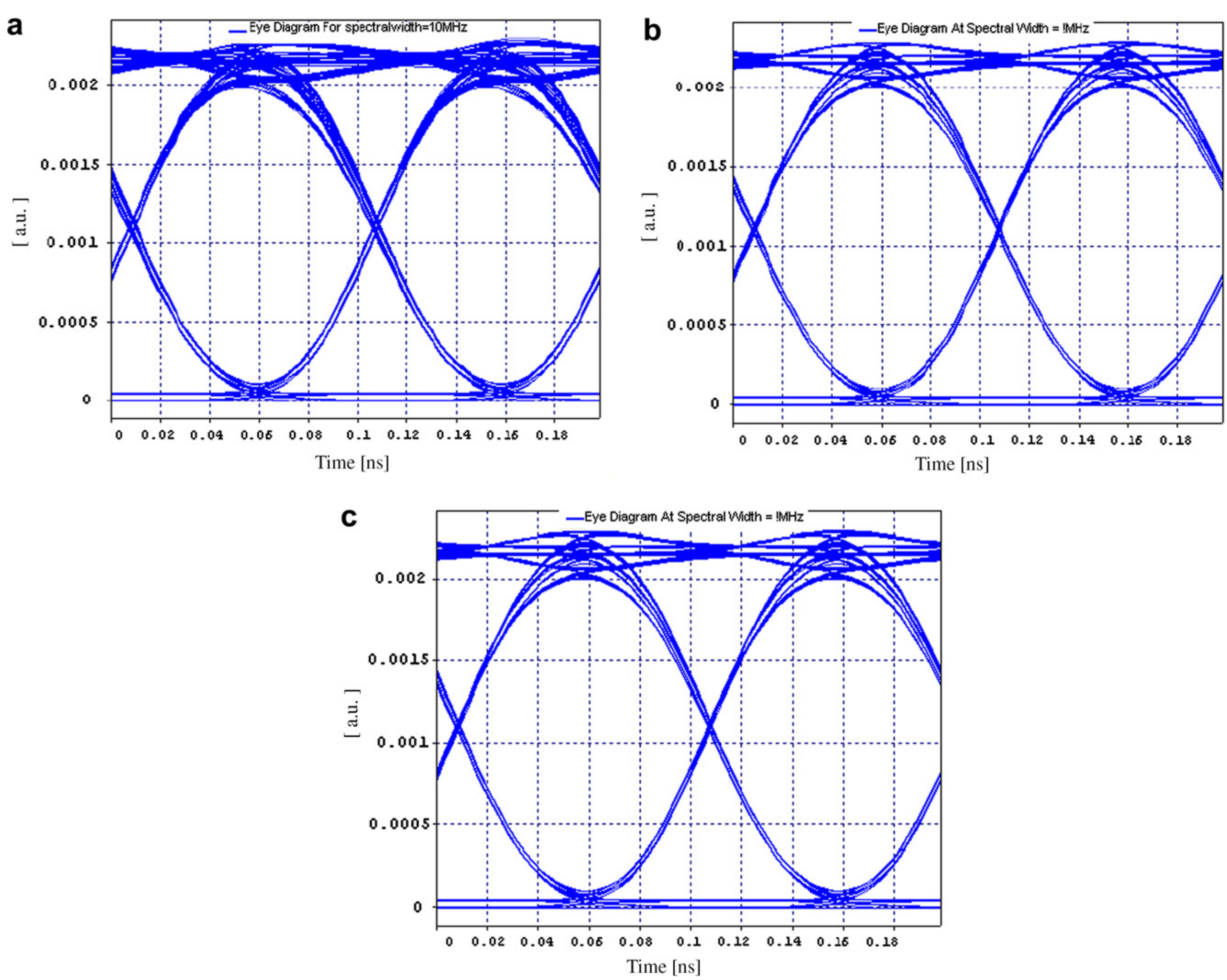

Fig. 8. Eye diagrams at different spectral widths (a) 10 MHz (b) 1 MHz (c) 100 kHz.

due to intensity noise under the individual impact of first- and second-order dispersion at different spectral widths and optical distances and graphically shown in Figs. 5 and 6. It reveals that the power penalty requirement is minimum with F_3 as compared with F_2 and reduces as we decrease the spectral width of the light source but increases as we increase the optical distance as discussed and proved above.

4. Section III: Experimental setup

This section provides the experimental proof of the results of the Section 2 and supports the fact that by reducing the spectral width of the light source in kHz range used at the transmitter section, we can minimize the effect of higher-order dispersion parameters over intensity noise and the power penalty. Hence, the optical distance can be increased and bit rate can be improved. In the experimental setup, we transmit two optical channels at the bit rate of 10 Gbps each with channel spacing of 0.05 THz i.e. the first channel is transmitted at the frequency of 193.025 THz and second one is transmitted at 193.075 THz at transmitting power of 6 mW. The information is transmitted in NRZ raised cosine format, which is modulated over light signal, emitted by CW Lorentzian laser, by using Sin2MZ modulator. The fiber parameters for this experiment setup are listed in Table 1.

From Fig. 7 it is clear that the power penalty required for compensating the intensity noise is less at spectral width of 100 kHz than 10 MHz and 1 MHz, which supports the results discussed previously in Section 2.

Further, Figs. 8 and 9 reveals that the eye opening at the spectral width of 100 kHz is more as compared to the eye opening at the spectral widths of 10 MHz and 1 MHz. Thus, using a laser of spectral width of 100 kHz can reduce the intersymbol interference introduced due to the dispersion. Also, reducing the spectral width of the laser, which also supports the results discussed previously, can increase the optical distance and Bit rate. Again Fig. 10 calculates the value of Q for different spectral widths, which reveals that the value of Q is also large at 100 kHz as compared to the spectral width of 10 MHz.

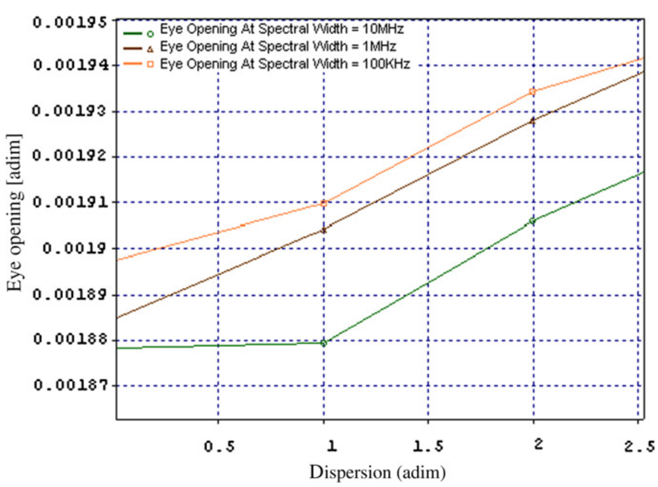

Fig. 9. Eye opening versus dispersion at different spectral width.

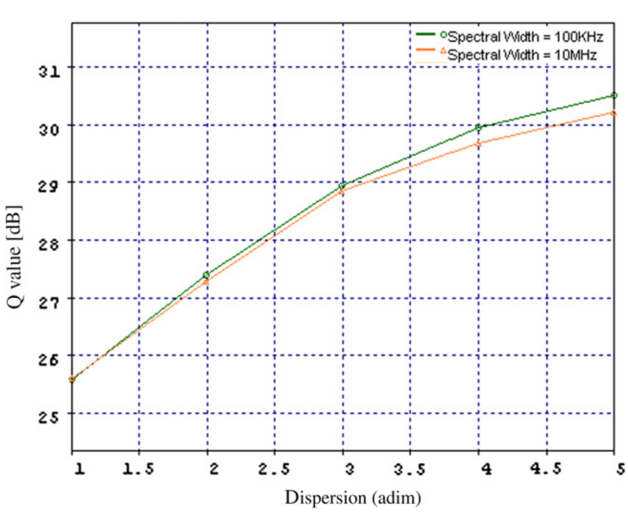

Fig. 10. Q value versus dispersion at different spectral widths.

5. Conclusion

From our calculations, we concluded that the individual effect of first-order dispersion and the combined effect of the first- and second-order dispersion parameters have same effect on the receiver intensity noise and power required to compensate this noise. On the other hand the effect of second-order dispersion parameter becomes effective with increasing optical length from 1000 km to 10,000 km. We further investigated that by reducing the spectral width to the kHz range, the effect of higher-order dispersion parameters can be reduced which increases the optical distance and the Bit rate of the optical system.

References

[1] J. Wang, K. Peterman, IEEE Journals of Light wave Technology 10 (1) (1992) 96.
[2] C. Crognale, IEEE Journals of Light wave Technology 15 (3) (1997) 482.
[3] E. Peral, IEEE Journals of Light wave Technology 18 (1) (2000) 84.
[4] K. Peterman, J. Wang, Electron Letter 27 (25) (1991) 2347.
[5] Ajay K. Sharma, R.K. Sinha, Shatendra K. Sharma, Sandeep K. Arya, R.S. Kaler, Journal of Optical Communications 25 (2004) 841.
[6] R.S. Kaler, Ajay K. Sharma, T.S. Kamal, Optical Fiber Technology 8 (2002) 295.
[7] K. Koyama, Y. Suematsu, IEEE Journals of Quantum Electron QE-21 (4) (1985) 292.
[8] A.F. Elrefaie, R.E. Wagner, D.A. Atlas, D.G. Daut, IEEE Journals of Light wave Technology 6 (1988) 704.
[9] Govind P. Aggarwal, Fiber Optic Communication System, third ed., Wiley Series.
[10] ITU-T, Rec.G.653, Characteristics of Dispersion Shifted Single Mode Optical Fiber Cable, 1992, p. 6.

[11] S. Yamamoto, N. Edagawa, H. Taga, et al., IEEE Journals of Light wave Technology LT-85 (1990) 1716.
[12] Adolfo Cartaxo, José Morgado, Journal of Light wave Technology 17 (1) (1999) 86.
[13] Adolfo Cartaxo, José Morgado, IEE Proceedings – Optoelectronics 145 (4) (1998) 211.
[14] José Morgado, Adolfo Cartaxo, in: Proceedings Conference SPIE – All-Optical Communication Systems: Architecture, Control and Network Issues III, vol. 3230, Dallas, USA, November 1997, p. 30.
[15] José Morgado, Adolfo Cartaxo, in: Proceedings of 10th Lasers and Electro-Optics Society Annual Meeting (LEOS ′97), vol. 3230, San Francisco, USA, November 1997, p. 295.