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Analysis of the impact of laser line width over RIN, power penalty and bit rate including higher-order dispersion in WDM systems

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Abstract

This paper investigated the effect of laser line width over relative intensity noise (RIN), power penalty and bit rate at optical distances in the range of 100–10,000 km both analytically and graphically. It is also proposed and analyzed that by reducing the laser line width to the range of KHz, we can minimize the impact of RIN and power penalty under the individual and combined impact of higher-order dispersion parameters.

Keywords: Laser line width; Bit rate; Power penalty; RIN and higher-order dispersion

1. Introduction

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. 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 line width of the light source.

Wang et al. [1] investigated the impact of dispersion terms on optical fiber communication systems using small signal analysis. Crognale et al. [2] extended the analysis of Wang by comparing the effect of second- and third-order dispersion terms. 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 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 a dispersive optical

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communication system. Moreover, this theory is applicable to evaluate the impact of higher-order dispersion on the small signal frequency response and relative intensity noise (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 were not reported in earlier work for higher-order dispersion terms. But the intensity noise and power penalty analysis at different line widths and at different bit rate up to 40 Gbps including first- and second-order dispersion terms were not reported in earlier work [1–11].

In this paper, we discussed the effect of laser line width of different laser over power penalty and RIN introduced in the optical system at different bit rates up to 40 Gbps under the individual and combined effects of first- and second-order dispersion parameters in an 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 impact of laser line width including the effect of second- and third-order dispersion parameters has been discussed analytically and briefly in Section 2 and shown graphically in Section 3.

2. 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

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

The input field can be transferred to the output field as

$$E_{\mathrm{o}}(\omega) = E_{\mathrm{out}}(\omega)\mathrm{e}^{\mathrm{i}\omega L} \tag{2}$$

With the slow varying complex field amplitude '$E_{\mathrm{o}}(t)$' at the fiber output, the propagation of a signal can be described in terms of propagation constant 'β' by the equation described in terms of Fourier transform as

$$E_{\mathrm{o}}(\omega) = E_{\mathrm{in}}(\omega)\mathrm{e}^{-\mathrm{i}\beta L} \tag{3}$$

Where the propagation constant in terms of Taylor series can be expanded as

$$\beta = \beta_{\mathrm{o}} + (\omega - \omega_{\mathrm{o}})\frac{\mathrm{d}\beta}{\mathrm{d}\omega} + \frac{1}{2}(\omega - \omega_{\mathrm{o}})^2\frac{\mathrm{d}^2\beta}{\mathrm{d}\omega^2} + \frac{1}{6}(\omega - \omega_{\mathrm{o}})^2\frac{\mathrm{d}^3\beta}{\mathrm{d}\omega^3} + \cdots \tag{4}$$

Here $\mathrm{d}\beta/\mathrm{d}\omega = \tau$ is the propagation delay per optical length.

Now

$$\beta = \beta_{\mathrm{o}} + (\omega - \omega_{\mathrm{o}})\tau + \frac{1}{2}(\omega - \omega_{\mathrm{o}})^2\frac{\mathrm{d}\tau}{\mathrm{d}\omega} + \frac{1}{6}(\omega - \omega_{\mathrm{o}})^3\frac{\mathrm{d}^2\tau}{\mathrm{d}\omega^2} + \cdots \tag{5}$$

where

$$\beta_2 = \text{first-order dispersion} = -\frac{\lambda^2}{2\pi c}\frac{\partial\tau}{\partial\lambda} \tag{6}$$

$$\beta_3 = \text{second-order dispersion} = \frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2\frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right] \tag{7}$$

Thus, by inserting Eq. (5) into Eq. (3), we have

$$E_{\mathrm{o}}(\omega) = E_{\mathrm{in}}(\omega)\mathrm{e}^{-\mathrm{i}\beta_{\mathrm{o}}L - \mathrm{i}L(\omega-\omega_{\mathrm{o}})\tau - \mathrm{i}L(1/2)(\omega-\omega_{\mathrm{o}})^2\frac{\partial\tau}{\partial\omega} - \mathrm{i}L(1/6)(\omega-\omega_{\mathrm{o}})^3(\partial^2\tau/\partial\omega^2)+\cdots} \tag{8}$$

As reported in [6], we neglect the phase and group delay i.e. $\beta_{\mathrm{o}}L$ and τ because both the terms produce only phase delay of the carrier signal and have no influence on the distortion on the signal. We define the following dispersion parameters as

$$F_2 = -\frac{L}{2}\frac{\mathrm{d}\tau}{\mathrm{d}\omega} = \frac{L}{2}\frac{\lambda^2}{(2\pi c)}\frac{\partial\tau}{\partial\lambda} \tag{9}$$

$$F_3 = \frac{L}{6}\frac{\mathrm{d}^2\tau}{\mathrm{d}\omega^2} = \frac{L}{2}\frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2\frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right] \tag{10}$$

Now, the output equation in terms of Fourier domain can be written by inserting Eqs. (9) and (10) into Eq. (8) as

$$E_{\mathrm{o}}(\omega) = \mathrm{e}^{[\mathrm{i}(\omega-\omega_{\mathrm{o}})^2F_2 - \mathrm{i}(\omega-\omega_{\mathrm{o}})^3F_3\ldots]}E_{\mathrm{in}}(\omega) \tag{11}$$

In time domain

$$\left(\mathrm{i}\omega = \frac{\partial}{\partial t}\right), \left((\mathrm{i}\omega)^2 = \frac{\partial^2}{\partial t^2}\right), \text{and}\left((\mathrm{i}\omega)^3 = \frac{\partial^3}{\partial t^3}\right)$$

Now, Eq. (11) becomes

$$E_{\mathrm{o}}(t) = \mathrm{e}^{[-\mathrm{i}F_2(\partial^2/\partial t^2) + F_3(\partial^3/\partial t^3)\ldots]}E_{\mathrm{in}}(t)\mathrm{e}^{\mathrm{i}\phi(t)} \tag{12}$$

Also,

$$E_{\mathrm{in}}(t) = \sqrt{P(t)}\mathrm{e}^{\mathrm{i}\phi(t)} \tag{13}$$

On inserting Eq. (13) into Eq. (12), we get

$$E_{\mathrm{o}}(t) = \mathrm{e}^{[\mathrm{i}F_2(\partial^2/\partial t^2) + F_3(\partial^3/\partial t^3)\ldots]}\sqrt{P(t)}\mathrm{e}^{\mathrm{i}\phi(t)} \tag{14}$$

But

$$E_{\mathrm{out}}(t) = E_{\mathrm{in}}(t) + \Delta E(t) \tag{15}$$

where $|\Delta E(t)| \ll |E_{\mathrm{in}}(t)|$

From Eqs. (14) and (15),

$$\Delta E(t) = [\mathrm{e}^{(-\mathrm{i}F_2(\partial^2/\partial t^2) + F_3(\partial^3/\partial t^3)\ldots)} - 1]\sqrt{P}\mathrm{e}^{\mathrm{i}\phi(t)} \tag{16}$$

Also,

$$P_{out}(t) = |E_{in}(t) + \Delta E(t)|^2 \approx |E_{in}(t)|^2 + 2\Re[E_{in}(t)\Delta E(t)] \quad (17)$$

Inserting Eqs. (13) and (15) into Eq. (17), we get

$$P_{out} = P + 2\Re[\sqrt{P(t)}e^{-i\phi(t)}(e^{(-iF_2(\partial^2/\partial t^2)+F_3(\partial^2/\partial t^2)+\cdots)} - 1)\sqrt{P(t)}e^{i\phi(t)}] \quad (18)$$

Express $e^x = 1 + x + x^2 \ldots = 1 + x$, because for PCM transmission, the spectrum due to noise is considered to be narrow. So, we get

$$P_{out}(t) = P + 2\Re\left[\sqrt{P(t)}e^{-i\phi(t)}\left(-iF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^2}{\partial t^2}\ldots\right)\sqrt{P(t)}e^{i\phi(t)}\right] \quad (19)$$

This equation can be expressed as

$$P_{out}(t) = P + \Delta P$$

where

$$\Delta P = 2\Re[\sqrt{P(t)}e^{-i\phi(t)}(e^{(-iF2(\partial^2/\partial t^2)+F3(\partial^3/\partial t^3)+\cdots)} - 1)\sqrt{P(t)}e^{i\phi(t)}] \quad (20)$$

For studying the transmission of PCM signals, we assume that the chip-free modulation can be achieved by using the external modulator. For this assumption, we have $dP/dt = 0$ at the decision point for both 1 and 0 bit. So, ΔP can be expressed as

$$\Delta P = 2Po(2F_2\phi'' - 3F_3\phi''\phi')$$

$$\frac{\Delta P^2}{Po^2} = 16F_2^2(\phi'')^2C + 36F_3^2(\phi'')^2(\phi') - 48F_2F_3(\phi'')^2(\phi') \quad (21)$$

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

$$r_{F_2F_3} = \frac{32}{3}F_2^2\pi^3\Delta v B^3 + \frac{144}{3}F_3^2\pi^4\Delta v^2B^2 - \frac{192}{3}F_2F_3\pi^4\Delta v^2B^2$$ = Intensity noise with combined effect of second- and third-order dispersion parameter (22)

$$r_{F_2} = \frac{32}{3}F_2^2\pi^3\Delta v B^3$$ = Intensity noise with individual effect of second-order dispersion parameter

$$r_{F_3} = \frac{144}{3}F_3^2\pi^4\Delta v^2 B^4$$ = Intensity noise with individual effect of third-order dispersion parameter

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

$$\delta_{pp} = -5\log_{10}\left[\frac{P(r_i)}{P(0)}\right] \quad (23)$$

where

$$P(r_i) = \frac{Q\sigma t + Q^2q\Delta f}{R(1 - r_i^2Q^2)}$$ = Power sensitivity with intensity noise 'r_i'

$$P(0) = \frac{Q\sigma t + Q^2q\Delta f}{R}$$ = Power sensitivity with intensity noise $r_i = 0$

where R is the responsivity ranges from 0.4 to 0.95, Q the digital SNR and it is assumed to be equal to 6.

3. Results and discussion

Referring to ITU-T Rec. 653 recommendation [8], we assume $\lambda_o = 1550$ nm, and $\frac{\partial^2\tau}{\partial\lambda^2} = 0.085\,\text{ps/nm}^2 - \text{km}$.

From Figs. 1–6, we observed that the RIN increases with the optical length ranging from 100 to 1000 km and also with the increase in bit rate ranging from 10 to 40 Gbps under the individual and combined effects of second- and third-order dispersion parameters at laser line width varying from 10 MHz to 100 KHz. Under the combined effect of second- and third-order dispersion parameters, i.e. $(F_2 + F_3)$, the intensity noise increases to a very large amount as illustrated by Figs. 1–3. Under the individual effect of F_3, the intensity noise is very small and increases at a very small rate with optical distance up to 1000 km at a bit rate of 10 Gbps. But, the intensity noise increases comparatively at a high rate as the optical distance increases to 10,000 km and the bit rate increases to 40 Gbps as revealed in Figs. 4–6. From Figs. 1–6, it is also observed that as we reduce the line width to 100 KHz, RIN reduces, which further reduces the power required to compensate this noise, and thus a high bit rate optical system can be designed economically.

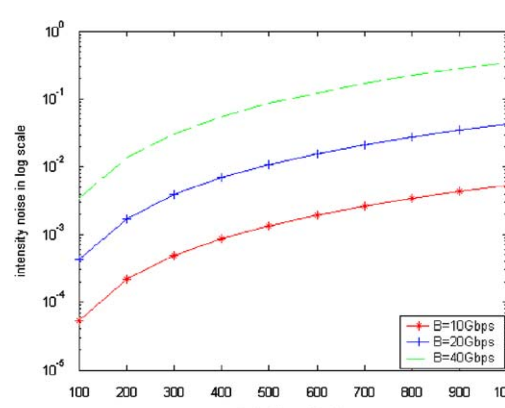

Fig. 1. Intensity noise versus optical length at different bit rates with laser line width of 100 KHz with combined effect of second- and third-order dispersions.

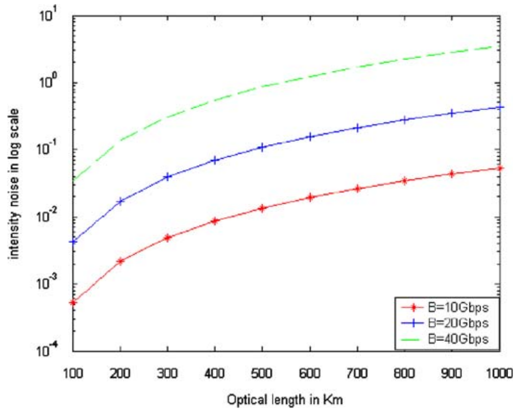

Fig. 2. Intensity noise versus optical length at different bit rates with laser line width of 1 MHz with combined effect of second- and third-order dispersions.

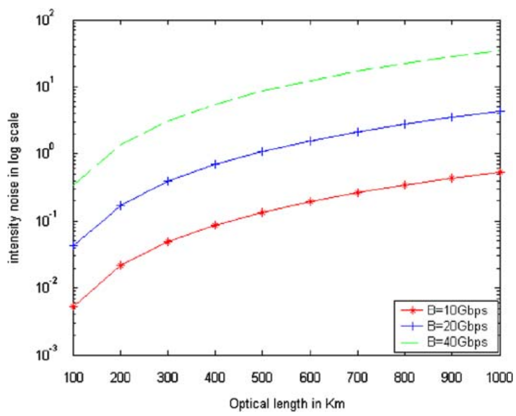

Fig. 3. Intensity noise versus optical length at different bit rates with laser line width of 10 MHz with combined effect of second- and third-order dispersions.

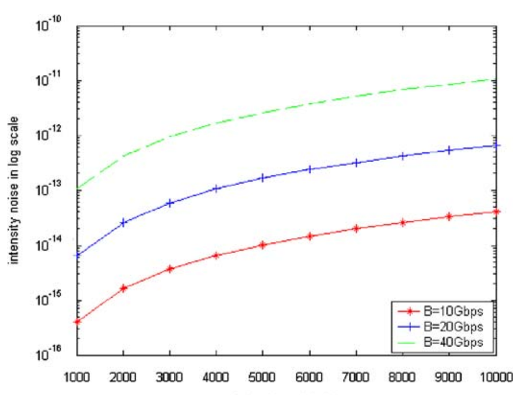

Fig. 4. Intensity noise versus optical length at different bit rates with laser line width of 100 KHz with individual effect of third-order dispersion only.

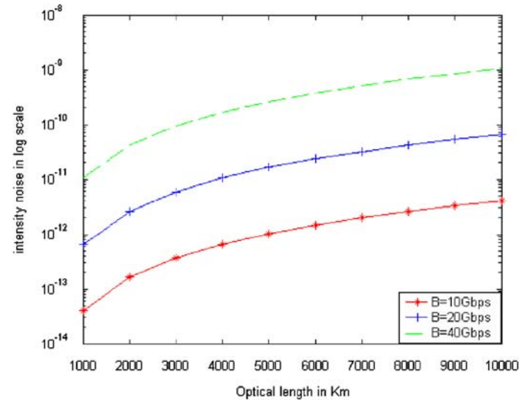

Fig. 5. Intensity noise versus optical length at different bit rates with laser line width of 1 MHz with individual effect of third-order dispersion only.

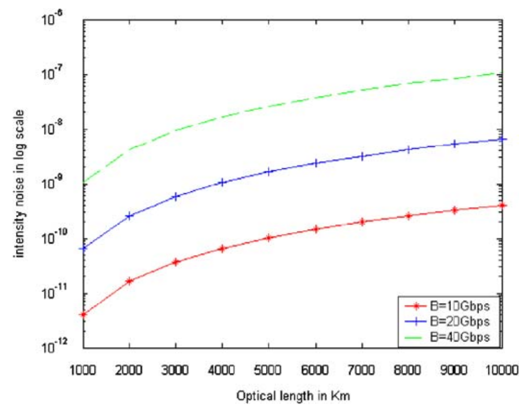

Fig. 6. Intensity noise versus optical length at different bit rates with laser line width of 10 M Hz with individual effect of third-order dispersion only.

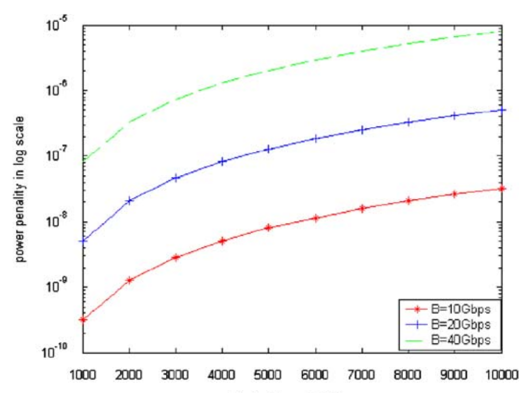

Fig. 7. Power penalty versus optical length at different bit rates with laser line width of 10 MHz with individual effect of third-order dispersion only.

Further, in Figs. 7–9, we calculate the amount of power penalty required to compensate the loss introduced in the optical system due to intensity noise at different bit rates ranging from 10 to 40 Gbps under the individual impact of third-order dispersion at different line widths and optical distances. It reveals that the

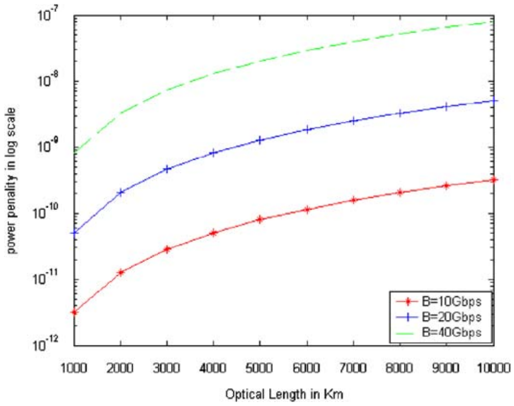

Fig. 8. Power penalty versus optical length at different bit rates with laser line width of 1 MHz with individual effect of third-order dispersion only.

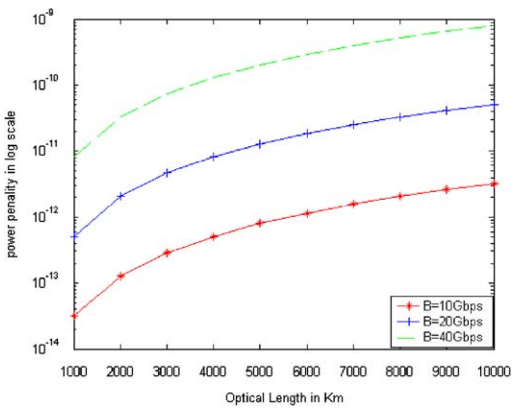

Fig. 9. Power penalty versus optical length at different bit rates with laser line width of 100 KHz with individual effect of third-order dispersion only.

power penalty requirement for F_3 increases as we increase the optical distance and bit rate but reduces as we decrease the line width of the light source.

4. Conclusion

From our calculations discussed in Section 3, we concluded that by reducing the laser line width to the KHz range, the effect of higher-order dispersion parameters on the RIN, bit rate and power required to compensate this RIN can be reduced. Therefore, a high bit rate long haul optical communication system can be achieved. We, further investigated that the third-order dispersion parameter becomes effective on increasing the optical length from 1000 to 10,000 km and on increasing the bit rate from 10 to 40 Gbps.

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