

MODELING THE EFFECTS OF CHROMATIC DISPERSION AND SELF-PHASE MODULATION IN OPTICAL FIBERS

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ABSTRACT

A theoretical analysis is presented to evaluate the performance deterioration of an optical transmission system due to the combined effects of chromatic dispersion (CD) and self-phase modulation (SPM), the performance of the system is assessed in terms of pulse broadening factor (PBF). Computed results are evaluated at different bit rates and input power. Results show that the linear dispersive mechanism is independent of power and as the input power or bit rate increases the nonlinear effect highly deteriorates the performance of system.

Key words: Self-Phase Modulation (SPM), Chromatic Dispersion (CD), Pulse broadening factor (PBF).

1. INTRODUCTION

To implement and meet the high bandwidth demand of today's applications like video on demand, video conferencing, digital photography etc, the spacing between successive pulses and the pulse duration of the signals decreases [1]. However, the short optical pulses are not monochromatic which leads to different arrival time for different wavelength components through the optical fiber and results chromatic dispersion (CD). Moreover at high bit rates (≥ 10 Gb/s), higher transmitted power is required that causes nonlinear effects [2], self-phase modulation (SPM) occurs when a phase modulation across a pulse is as a result of its own intensity variation thus broadening the optical spectrum of the pulse which again enhances or decreases the CD effect. As the channel bit rate increases to 10 Gb/s and beyond, pulses disperse and encounter nonlinearity with propagation and start to spill into the adjacent bit slots due to the combined effects of CD and SPM that lead to significant signal degradation, inter-symbol interference and increases bit error rate (BER) of the system [3]-[5]. The effects of SPM and CD on pulse propagation has been the subject of considerable research interest during the last decade, a number of research works have been carried out to

evaluate the impact of CD and SPM by using different approaches [5]-[7]. Slakhove [8], evaluated the effects of SPM based on BER performance of an optical heterodyne continuous phase frequency shift keying (CPFSK) transmission system.

In this paper a mathematical model is presented for pulse broadening factor (PBF) which is the final to initial RMS pulse width ratio, to describe the effects of CD and SPM on an optical pulse propagating inside a single-mode fiber modeled as a nonlinear dispersive medium. It is observed that at high bit rates pulse broadening induced by SPM and CD can be quite large and the pulse width may exceed the minimum width limitation required for successful reception of information.

2. MATHEMATICAL ANALYSIS

When the optical field is assumed to maintain its polarization, the evolution of slowly varying electric field can be described by a single nonlinear Schrödinger equation, which takes into account both dispersion and nonlinearity [8].

$$i \frac{\partial}{\partial z} A = -i \frac{\alpha}{2} A + \frac{\beta_2}{2} \frac{\partial^2}{\partial^2 t} A + i \frac{\beta_3}{6} \frac{\partial^3}{\partial^3 t} A - \gamma |A|^2 A \quad (1)$$

Where z is the longitudinal coordinate of the fiber, t is the time in a framework moving at the group velocity, A is the complex electrical field envelope, β_2 is the first-order CD, β_3 second-order CD, α the power absorption coefficient, and γ is the nonlinear coefficient.

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

$$t = T - z/v_g$$

If the optical wavelength is not too close to zero dispersion wavelengths, the first-order CD dominates and (1) can be written as

$$i \frac{\partial}{\partial z} A = -i \frac{\alpha}{2} A + \frac{\beta_2}{2} \frac{\partial^2}{\partial^2 t} A - \gamma |A|^2 A \quad (2)$$

(2) require numerical solution in order to asses the combined effects of dispersion and nonlinearity on pulse propagation. However an analytic expression can be predicted based on the assumption, that the incident field is multiplied by an intensity dependent phase factor θ_{eff} , that is arising from nonlinear effects such as (SPM) and that the resulting field propagates as if the medium is linear but dispersive.

Let, the incident field at $z = 0$ is of the form

$$A(0, t) = A_0 f(t) \quad (3)$$

where A_0^2 is the peak power and $f(t)$ is the pulse shape. To add the effect of nonlinearity on pulse propagation $A(0, t)$ is replaced by a field that contain a phase factor θ_{eff} arising from SPM.

$$A_{eff}(0, t) = A_0 f(t) \exp(i\theta_{eff}) \quad (4)$$

where θ arises from SPM. θ can be obtained by using (2) with $\beta_2=0$

$$i \frac{\partial}{\partial z} A = -i \frac{\alpha}{2} A - \gamma |A|^2 A \quad (5)$$

(5) was solved exactly in [16] by writing

$$A = r \exp(i\theta)$$

Equating real and imaginary parts we obtain.

$$r(z, t) = r_0(t) \exp\left(-\frac{\alpha}{2} z\right) \quad (6)$$

$$\theta(z, t) = \theta_0(t) + \gamma r_0^2(t) L_{eff} \quad (7)$$

where, $r_0(t) = A_0 f(t)$, $L_{eff} = \frac{1-e^{-\alpha z}}{\alpha}$ and the phase shift after distance z is given by

$$\theta_{eff} = \gamma A_0^2 f^2(t) L_{eff} = \theta_m f^2(t) \quad (8)$$

where $\theta_m = \gamma A_0^2 L_{eff}$ is the maximum phase shift that occurs at $t = 0$.

Substituting (8) in (4) we obtain the input field that is affected by the SPM.

$$A_{eff}(0, t) = A_0 f(t) \exp\{i\theta_m f^2(t)\} \quad (9)$$

In order to obtain the effect of dispersion on a pulse that is affected by SPM we can use (9) as an effective field.

Since attenuation has no effect on dispersion, the effect of dispersion on a pulse that encounters the effect of SPM can be obtained by solving (2) with $\gamma = 0$, $\alpha = 0$ and A_{eff} as input field at distance $z = 0$ which then becomes

$$i \frac{\partial}{\partial z} A_{eff} = \frac{\beta_2}{2} \frac{\partial^2}{\partial t^2} A_{eff} \quad (10)$$

(10) can be solved by using the Fourier transform method if $\tilde{A}_{eff}(z, \omega)$ is the Fourier transform of $A_{eff}(z, t)$ such that

$$A_{eff}(z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{A}_{eff}(z, \omega) \exp(-i\omega t) d\omega \quad (11)$$

then it satisfies an ordinary differential equation of the form

$$i \frac{\partial}{\partial z} \tilde{A}_{eff} = -\frac{\beta_2}{2} \omega^2 \tilde{A}_{eff}$$

So, the solution of (2) in frequency domain is

$$\begin{aligned} A(z, \omega) &= F[A_{eff}(0, t)] \exp(i/2 \beta_2 \omega^2 z) \\ &= F\{A_0 f(t) \exp[i\theta_m f^2(t)]\} \exp(i/2 \beta_2 \omega^2 z) \\ &= A_0 F\{f(t) \exp[i\theta_m f^2(t)]\} \exp(i/2 \beta_2 \omega^2 z) \end{aligned} \quad (12)$$

(12) shows that the effect of CD changes the phase of each of the spectral components of the pulse by an amount that depends on both frequency and propagation distance, even though such phase change do not affect the pulse spectrum, they can modify the pulse shape.

Now consider a pulse whose shape is Gaussian which is defined as,

$$f(t) = \exp\left(-\frac{t^2}{2T_0^2}\right) \quad (13)$$

where T_0 is the half width at $1/e$ intensity point which is related to the full width at half maximum (FWHM) by

$$T_{FWFM} = 2\sqrt{2\ln 2} T_0 \quad (14)$$

Substituting (13) in (12), we obtain

$$A(z, \omega) = F\left\{\exp\left(-\frac{t^2}{2T_0^2}\right) \exp\left[i\theta_m \exp\left(-\frac{t^2}{T_0^2}\right)\right]\right\} \exp(i/2 \beta_2 \omega^2 z) \quad (15)$$

where

$$\Psi(\omega) = F\left\{\exp\left(-\frac{t^2}{2T_0^2}\right) \exp\left[i\theta_m \exp\left(-\frac{t^2}{T_0^2}\right)\right]\right\} \quad (16)$$

Represents the spectral width of the pulse that encounters the effects of SPM.

Let,

$$\zeta(t) = \exp\left(-\frac{t^2}{2T_0^2}\right) \exp\left[i\theta_m \exp\left(-\frac{t^2}{T_0^2}\right)\right] \quad (17)$$

So,

$$\Psi(\omega) = F[\zeta(t)] \quad (18)$$

The RMS bandwidth of the pulse is defined as

$$(\Delta\omega)^2 = \langle\omega^2\rangle - \langle\omega\rangle^2$$

$$(\Delta\omega)^2 = \frac{\int_{-\infty}^{\infty} \omega^2 |\Psi(\omega)|^2 d\omega}{\int_{-\infty}^{\infty} |\Psi(\omega)|^2 d\omega} - \left[\frac{\int_{-\infty}^{\infty} \omega |\Psi(\omega)|^2 d\omega}{\int_{-\infty}^{\infty} |\Psi(\omega)|^2 d\omega} \right]^2 \quad (19)$$

Since $F[\zeta(t)]$ cannot be evaluated in closed form we use the following properties of Fourier transform in (19).

multiplication property

$$\int_{-\infty}^{\infty} |\Psi(\omega)|^2 d\omega = \frac{1}{2\pi} \int_{-\infty}^{\infty} |\zeta(t)|^2 dt \quad (20)$$

frequency derivative and complex conjugation property

$$\int_{-\infty}^{\infty} \omega |\Psi(\omega)|^2 d\omega = \frac{i}{2\pi} \int_{-\infty}^{\infty} \zeta'(t) \zeta^*(t) dt \quad (21)$$

where $\zeta'(t)$ and $\zeta^*(t)$ represents time derivative and complex conjugation of $\zeta(t)$ respectively.

multiplication and frequency derivative property

$$\int_{-\infty}^{\infty} \omega^2 |\Psi(\omega)|^2 d\omega = \frac{1}{2\pi} \int_{-\infty}^{\infty} |\zeta'(t)|^2 dt \quad (22)$$

using (20), (21) and (22) in (19) the following expression is found for (19)

$$(\Delta\omega)^2 = \frac{\int_{-\infty}^{\infty} |\zeta'(t)|^2 dt}{\int_{-\infty}^{\infty} |\zeta(t)|^2 dt} + \left[\frac{\int_{-\infty}^{\infty} \zeta'(t) \zeta^*(t) dt}{\int_{-\infty}^{\infty} |\zeta(t)|^2 dt} \right]^2 \quad (23)$$

$$|\zeta(t)|^2 = \exp\left(-\frac{t^2}{T_0^2}\right) \quad (24)$$

$$\zeta'(t)\zeta^*(t) = -\frac{t[1 + 2i\theta_m \exp(-t^2/T_0^2)] \exp(-t^2/T_0^2)}{T_0^2} \quad (25)$$

$$|\zeta'(t)|^2 = \frac{t^2[1 + 4\theta_m^2 \exp(-t^2/T_0^2)] \exp(-t^2/T_0^2)}{T_0^4} \quad (26)$$

since,

$$\int_{-\infty}^{\infty} \zeta'(t)\zeta^*(t) dt = 0$$

$$\frac{\int_{-\infty}^{\infty} \zeta'(t)\zeta^*(t) dt}{\int_{-\infty}^{\infty} |\zeta(t)|^2 dt} = 0 \quad (27)$$

$$(\Delta\omega)^2 = \frac{\int_{-\infty}^{\infty} |\zeta'(t)|^2 dt}{\int_{-\infty}^{\infty} |\zeta(t)|^2 dt} \quad (28)$$

$$(\Delta\omega)^2 = \frac{1}{2T_0^2} \left(1 + \frac{4}{3\sqrt{3}} \theta_m^2 \right)$$

and the variance of the spectrum is

$$(\Delta\omega)^2 = \frac{1}{T_0^2} \left(1 + \frac{4}{3\sqrt{3}} \theta_m^2 \right) \quad (29)$$

since we are using Gaussian function as input pulse whose spectrum is also Gaussian, the effect of SPM will only change the width of the spectrum of the pulse. So, we can use (29) as the variance of (18).

Substituting (29) in (15) we obtain

$$A(z, \omega) = A_0 \exp \left[-\frac{1}{2} \frac{\omega^2 T_0^2}{(1 + 4/3\sqrt{3} \theta_m^2)} \right] \exp(i/2 \beta_2 \omega^2 z) \quad (30)$$

The time domain representation of (31) is

$$A(z, t) = \frac{1}{2\pi} A_0 \int_{-\infty}^{\infty} \exp \left[-\frac{1}{2} \frac{\omega^2 T_0^2}{(1 + 4/3\sqrt{3} \theta_m^2)} \right] \exp(i/2 \beta_2 \omega^2 z - i\omega t) d\omega \quad (31)$$

$$A(z, t) = A_0 \frac{\exp \left\{ -\frac{1}{2} \frac{(9 + 4\sqrt{3}\theta_m^2)t^2}{[9T_0^2 - i\beta_2 z(9 + 4\sqrt{3}\theta_m^2)]} \right\} (9 + 4\sqrt{3}\theta_m^2)^{1/2}}{\sqrt{2\pi} \{9T_0^2 - i\beta_2 z(9 + 4\sqrt{3}\theta_m^2)\}^{1/2}} \quad (32)$$

let,

$$A(z, t) = Q(z)h(z, t) \quad (33)$$

where, $Q(z)$ represents the amplitude of the pulse at distance Z .

$$Q(z) = A_0 \frac{(9 + 4\sqrt{3}\theta_m^2)^{1/2}}{\sqrt{2\pi} \{9T_0^2 - i\beta_2 z(9 + 4\sqrt{3}\theta_m^2)\}^{1/2}}$$

and $h(z, t)$ represents the shape of the pulse at distance Z , that encounters the effects of SPM and CD simultaneously

$$h(z, t) = \exp \left\{ -1/2 \frac{(9 + 4\sqrt{3}\theta_m^2)t^2}{[9T_o^2 - i\beta_2 z(9 + 4\sqrt{3}\theta_m^2)]} \right\}$$

the RMS pulse width at distance z is defined as

$$\Delta t(z) = [\langle t^2 \rangle - \langle t \rangle^2]^{1/2} \quad (34)$$

where, $\langle t^n \rangle$ is the n^{th} moment defined as

$$\langle t^n \rangle = \frac{\int_{-\infty}^{\infty} t^n |A(z, t)|^2 dt}{\int_{-\infty}^{\infty} |A(z, t)|^2 dt} \quad (35)$$

where, $|A(z, t)|^2 = A(z, t)A^*(z, t)$, and $A^*(z, t)$ denotes the complex conjugation of $A(z, t)$, since $Q(z)$ represents amplitude and is constant we can neglect it to determine $\langle t^n \rangle$, hence (35) can be written as

$$\langle t^n \rangle = \frac{\int_{-\infty}^{\infty} t^n |h(z, t)|^2 dt}{\int_{-\infty}^{\infty} |h(z, t)|^2 dt} \quad (36)$$

where, $|h(z, t)|^2 = h(z, t)h^*(z, t)$, and $h^*(z, t)$ denotes the complex conjugation of $h(z, t)$

$$h(z, t) = \exp \left\{ -1/2 \frac{(1 + 4/3\sqrt{3}\theta_m^2)t^2}{T_o^2[1 - i\beta_2 z/T_o^2(1 + 4/3\sqrt{3}\theta_m^2)]} \right\}$$

Let, $\mathbb{L} = \beta_2 z/T_o^2$

$$h(z, t) = \exp \left\{ -1/2 \frac{(1 + 4/3\sqrt{3}\theta_m^2)t^2}{T_o^2[1 - i\mathbb{L}(1 + 4/3\sqrt{3}\theta_m^2)]} \right\} \quad (37)$$

$$h^*(z, t) = \exp \left\{ -1/2 \frac{(1 + 4/3\sqrt{3}\theta_m^2)t^2}{T_o^2[1 + i\mathbb{L}(1 + 4/3\sqrt{3}\theta_m^2)]} \right\} \quad (38)$$

$$|h(z, t)|^2 = \exp \left\{ -\frac{(1 + 4/3\sqrt{3}\theta_m^2)t^2}{T_o^2[1 + \mathbb{L}^2(1 + 4/3\sqrt{3}\theta_m^2)^2]} \right\} \quad (39)$$

$$\int_{-\infty}^{\infty} t^2 |h(z, t)|^2 dt = \frac{\sqrt{\pi}}{6\sqrt{3}} \frac{T_o^3(27 + 27\mathbb{L}^2 + 24\sqrt{3}\mathbb{L}^2\theta_m^2 + 16\mathbb{L}^2\theta_m^4)^{3/2}}{(9 + 4\sqrt{3}\theta_m^2)^{3/2}} \quad (40)$$

$$\int_{-\infty}^{\infty} |h(z, t)|^2 dt = \frac{\sqrt{\pi}}{\sqrt{3}} \frac{T_o(27 + 27\mathbb{L}^2 + 24\sqrt{3}\mathbb{L}^2\theta_m^2 + 16\mathbb{L}^2\theta_m^4)^{1/2}}{(9 + 4\sqrt{3}\theta_m^2)^{1/2}} \quad (41)$$

Since

$$\int_{-\infty}^{\infty} t |h(z, t)|^2 dt = \int_{-\infty}^{\infty} t \exp \left\{ -\frac{(1 + 4/3\sqrt{3} \theta_m^2) t^2}{T_0^2 [1 + L^2 (1 + 4/3\sqrt{3} \theta_m^2)^2]} \right\} dt = 0$$

$$\Delta t(z) = \frac{T_0}{\sqrt{2}} \left[\frac{27 + 27L^2 + 24\sqrt{3}L^2\theta_m^2 + 16L^2\theta_m^4}{3(9 + 4\sqrt{3}\theta_m^2)} \right]^{1/2}$$

The initial RMS width of the pulse is $\Delta t_0 = \frac{T_0}{\sqrt{2}}$

So, the pulse broadening factor which is the ratio of final to initial RMS pulse width is

$$\hat{U} = \frac{\Delta t(z)}{\Delta t_0} = \left[\frac{1 + L^2 + \frac{24}{9\sqrt{3}}L^2\theta_m^2 + \frac{16}{27}L^2\theta_m^4}{\left(1 + \frac{4}{3\sqrt{3}}\theta_m^2\right)} \right]^{1/2} \quad (42)$$

(42) describes the pulse broadening factor for an initial Gaussian pulse that experience the effects of CD and SPM simultaneously during propagation through an optical fiber.

In the absence of SPM $\theta_m = 0$ and the above equation can be used to determine the pulse broadening factor caused by the effect of chromatic dispersion (CD) only.

$$\hat{U} = \frac{\Delta t(z)}{\Delta t_0} = [1 + L^2]^{1/2} \quad (43)$$

3. RESULTS AND DISCUSSIONS

Following the theoretical analysis presented in section 2, performance results of an optical transmission system is evaluated in this section. The results are carried out in terms of pulse broadening factor for a Gaussian pulse profile, that encounters the effects of Self-Phase modulation and Chromatic Dispersion simultaneously, the results are evaluated at different bit rates and input power for the fiber parameters presented in table-1.

Table-1: Fiber parameters

Parameters (unit)	Values
Nonlinear refractive index, n_2 (m ² /w)	2.35×10^{-20}
Bit rates, B (Gb/s)	10 - 40
Wavelength, λ (nm)	1550
Attenuation coefficient, α (dB/km)	0.25
Input power, P_i (mW)	30 - 60
Effective area, A (m ²)	5.5×10^{-11}
Dispersion parameter, β_2 (ps ² /km)	-20.39
Fiber length, (km)	Varied

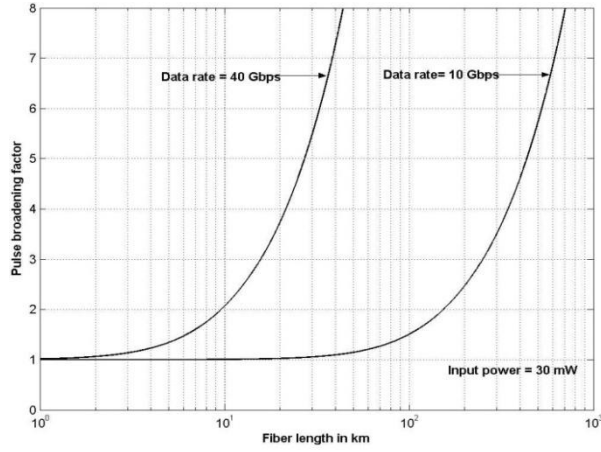


Fig. 1: Pulse broadening factor versus fiber link length.

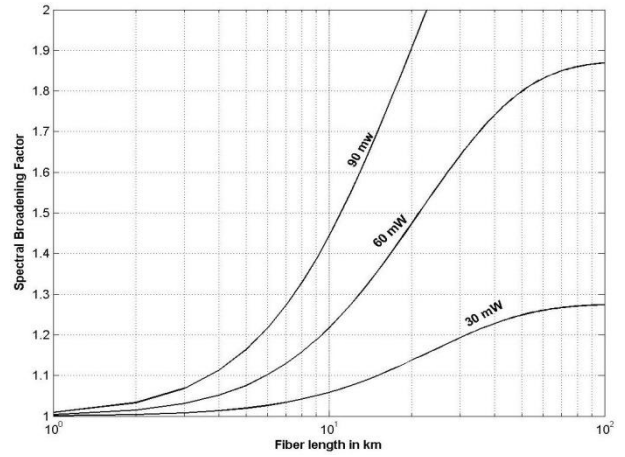


Fig. 2: Spectral broadening factor with varying link length and Input power.

Pulse broadening factor versus fiber length is shown in Fig. 1. From the figure it is observed that broadening factor increases with an increase of data rate. This phenomenon occurs due to the fact that as the data rate increases the spectral width of the pulse increases, since each frequency components of the pulse travel at different velocity due to the effect of chromatic dispersion they travel the same distance at different time result temporal spreading of the pulse through the effect of chromatic dispersion.

Fig. 2 shows the dependence of input power and transmission length on pulse spectra caused by the effect of Self-Phase modulation (SPM). From the figure it is observed that as the input power increases the spectral broadening factor also increases, since the effect of nonlinearity increases with the input power. The spectral broadening factor increases with distance this occurs from the fact that new frequency components are generated continuously by SPM as the pulse propagates down the fiber. From the above figure it is observed that at 10 km the spectral broadening factors are 1.050, 1.21 and 1.43 for 30 mW, 60 mW and 90 mW input power respectively.

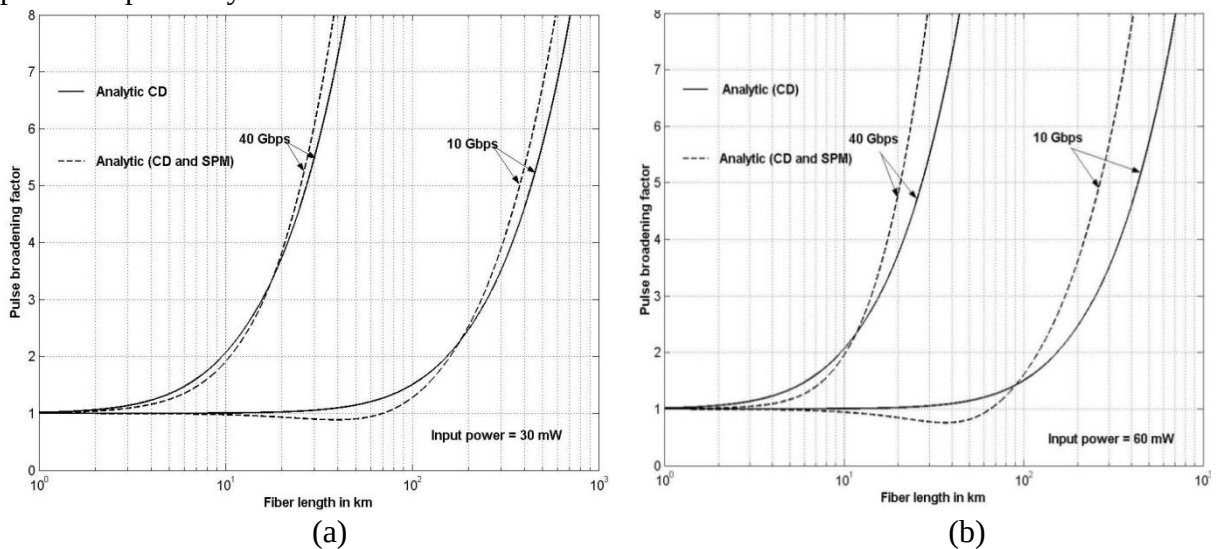


Fig. 3: Pulse broadening factor as a function of link length for different bit rates at (a) 30 mW input power (b) 60 mW input power.

Fig. 3. depicts comparative pulse broadening factor between linear dispersive case (Considering chromatic dispersion only) and nonlinear dispersive case (Considering the combined effects of self-phase modulation and chromatic dispersion) for two different input power 30 mW and 60 mW. The simulation is carried out at two different bit rates 10 Gbps and 40 Gbps. From the above figures it is observed that the pulse get compressed up to some distance due to the combined effects of SPM and CD after which the broadening rate of the pulse in the nonlinear dispersive case is greater than the broadening rate caused by CD alone this is because as the pulse propagates down the fiber new frequency components are generated by the effects of SPM which enhances the temporal broadening of the pulse through the effect of CD. It is also observed from fig. 3(a) and fig. 3(b) that for the same data rate pulse broadening factor is same for dispersive case but they are different for nonlinear dispersive case. This phenomenon can be described by the fact that input power has no effect on chromatic dispersion but an increase of power enhances the effect of SPM which enhances pulse broadening through the effect of chromatic dispersion.

4. CONCLUSION

A detailed theoretical analysis is carried out to get an expression of pulse broadening factor for a pulse that is affected by the combined effects of chromatic dispersion and self-phase modulation (SPM) in an optical fiber communication system. While analyzing the effect of chromatic dispersion on pulse broadening it is found that the pulse broadening factor increases with an increase of bit rate. It has observed that the impact of self-phase modulation depends on the input power as well as transmission link length as the input power or fiber length increases spectral broadening factor induced by SPM also increases. The combined effect of SPM and CD shows a different behavior on pulse propagation the pulse get compressed up to a fixed distance due to the interplay between SPM and CD as a result up to this distance the broadening factor is less than the broadening factor induced by chromatic dispersion only. After this length the pulse broaden more rapidly compared to the broadening caused by CD.

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