Available online at www.sciencedirect.com
ScienceDirect
Optik 120 (2009) 356–363
Optik Optics
www.elsevier.de/ijleo

A long-haul wavelength division multiplexed system using standard single-mode fiber in presence of self-phase modulation

Muhammad Anisuzzaman Talukder, Mohammed Nazrul Islam*

Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

Received 27 June 2006; accepted 15 February 2007

Abstract

Performance of a long-haul wavelength division multiplexed (WDM) communication system has been evaluated in presence of nonlinear effects using standard single-mode fiber. Different compensation configurations, namely, post-, pre- and bi-end compensation, have been investigated to mitigate the fiber nonlinear effects. Eye-opening degradation due to mutual interplay between self-phase modulation (SPM) and group velocity dispersion for the compensating techniques has been estimated with respect to the transmission length and the residual dispersion in case of WDM system. Maximum threshold power levels at the bit error rate of 10^{-9} limited by the SPM effect have been determined. From a comparison among the compensating techniques, bi-end compensation configuration has been found to be the most suitable technique for any fiber length in case of a WDM communication system.

Keywords: Dispersion compensation; Group velocity dispersion; Self-phase modulation; Single-mode fiber

1. Introduction

Periodical insertion of in-line erbium-doped fiber amplifiers (EDFAs) provides the opportunity to transmit optical pulses in a long fiber link irrespective of the loss. But for a transmission link using standard single-mode fiber (SMF), group velocity dispersion (GVD) causes the transmitted pulse to broaden and distort so much that it eventually limits the transmission distance. Nevertheless, a variety of dispersion-compensating techniques have been proposed and investigated for constructing long-distance transmission systems [1–5]. In the dispersion-compensating technique using dispersion-compensating fiber (DCF), the nonzero anomalous GVD of SMF is periodically compensated by the proper length of DCF placed at the input, output or both ends of the compensation interval and are termed as pre-end compensation configuration (PRCC), post-end CC (POCC) and bi-end CC (BECC), respectively. Then, in a DCF system, the bandwidth-length product of the transmission link is no longer limited by the GVD rather by the mutual interplay between the dispersion and the nonlinear effects of fiber. Among several fiber nonlinear effects, the most dominant effect in a standard SMF is the self-phase modulation (SPM), which is caused by the nonlinear dependence of the refractive index on pulse intensity [6]. Since high-speed data transmission systems require significantly large amount of received power for error-free detection, the performance of dispersion-compensated link is eventually limited by the interaction

*Corresponding author.
E-mail addresses: anistal@eee.buet.ac.bd (M.A. Talukder), nazrul@eee.buet.ac.bd (M.N. Islam).

0030-4026/$ - see front matter
doi:10.1016/j.ijleo.2007.02.013

of SPM and the fiber dispersion. The interaction of SPM with fiber dispersion depends on the DCF position in a dispersion-compensated scheme as well.

Again, in a wavelength division multiplexed (WDM) system, it is difficult to compensate all the transmission channels completely for dispersion [7,8]. If perfect dispersion compensation is accomplished for a particular channel of the WDM system, other wavelength channels will encounter with different amount of cumulative dispersion proportional to their wavelength separations from the zero-average-dispersion wavelength channel. On the other hand, to suppress the four-wave mixing (FWM) effect, it is recommended that the GVD effect must not be completely compensated [9,10]. Mutual interplay between SPM and GVD is different in case of partial compensation than that of complete compensation. The degree of SPM effect even varies with the sign and amount of residual dispersion.

The effect of SPM in a dispersion-compensated fiber link has drawn research interest recently [11–13]. A single channel system has been studied with lumped dispersion compensation but without any EDFA in the line of transmission, which shows that the PRCC scheme is preferable to the POCC scheme in case of complete compensation [11]. Investigation of a terrestrial 5×100 km WDM system has been carried out in Ref. [12] where the dispersion and fiber loss are compensated periodically and the POCC scheme is turned out to be the suitable dispersion-compensating technique for practical implementation as compared to the PRCC scheme. However, the amplified spontaneous emission (ASE) noise due to EDFA is not considered in the study. Also to the best of the authors' knowledge, the BECC scheme has not yet been investigated and compared with the POCC and PRCC schemes in case of long-haul WDM system. Therefore, the objective of the paper is to develop a numerical study on the transmission performance of all the compensation schemes, namely, POCC, PRCC and BECC. The receiver performance is evaluated considering the eye-opening degradation due to the mutual interplay of GVD and SPM, where all the noise sources including ASE noise of in-line EDFAs are taken into account. Finally, a performance comparison is made among the three compensation schemes in order to find the most efficient scheme for practical WDM system.

2. Theoretical model

At the modest input power level, the SMF behaves as a dispersive and linear medium, where the transmitted spectrum does not change during propagation. Only the pulse gets weaker due to attenuation and broadened in the time domain by the second- and third-order dispersion. In a dispersion-compensated link consisting of a standard SMF and a DCF, the input pulses first broaden due to propagation through the SMF and then subsequently recompress to their original shape due to propagation through the DCF, which has the dispersion coefficient parameter of opposite sign to that of SMF. As the input power is increased, the fiber nonlinear effects, especially SPM, affect significantly the pulse dynamics in the transmission link. During the propagation of a pulse through the fiber, the GVD changes the frequency across the pulse referred to as frequency chirp. The chirp $\delta\omega$ depends on the sign of the dispersion parameter. If the dispersion coefficient parameter of the fiber is negative, the frequency increases across the pulse from the leading to the trailing edge that is referred to as the positive frequency chirp. On the other hand, the frequency chirp is negative, i.e., the frequency decreases across the pulse from the leading to the trailing edge if the dispersion coefficient parameter is positive. The frequency chirp is also induced by the SPM effect and increases in magnitude with the propagated distance. Frequency chirping is positive due to the SPM effect irrespective of the sign of the dispersion coefficient parameter. Therefore, the SPM effect leads to an enhanced rate of pulse broadening in the fiber with negative dispersion coefficient parameter compared to that expected from the GVD alone. However, the broadening rate decreases during propagation in the fiber with positive dispersion coefficient parameter, as the two chirp contributions cancel each other.

The nonlinear Schrodinger equation (NLSE) can be modified to include higher-order dispersion, which has been found successful in accurately modeling the pulse propagation in SMF for many diverse applications [14,15]. The modified NLSE incorporating the effects of fiber loss, SPM and GVD is given by [6]

$$\mathrm{i}\frac{\partial A}{\partial z} = -\frac{\mathrm{i}}{2}\alpha A + \frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{\mathrm{i}}{6}\beta_3\frac{\partial^3 A}{\partial T^3} - \gamma|A|^2 A, \tag{1}$$

where A is the slowly varying amplitude of the pulse envelope, z is the longitudinal coordinate and T is the time measured in a frame of reference moving with the pulse at the group velocity v_g, $T = t - z/v_g$. The fiber nonlinearity affects the wave equation through the nonlinear parameter γ. In Eq. (1) the dispersion and dispersion slope parameters are represented by β_2 and β_3, respectively, and α is the loss coefficient. γ is related to the nonlinear-index coefficient n_2 by

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

where A_{eff} is the effective core area of the fiber.