ELectronics EXpress

IEICE Electronics Express, Vol.1, No.13, 386–391

40 Gbit/s polarization modulation in ultra-long haul transmission systems by using optical phase conjugators

Andy L. Y. Low,[a] **Y. K. Chan, S. F. Chien, A. H. You, and T. S. Guan**

Faculty of Engineering & Technology, Multimedia University

Jalan Ayer Keroh Lama, 75450 Melaka, Malaysia.

a) *andy@mmu.edu.my*

Abstract: In this paper, we present a numerical investigation on the performance of 40 Gbit/s polarization modulation (POLSK) in ultra-long haul transmission systems by using optical phase conjugator (OPC). The effects of both semiconductor optical amplifier (SOA) and dispersion shifted fiber (DSF) based OPCs on the 10,000 km system are investigated. It is found that only 53 SOA based OPCs are needed in order to achieve the bit-error-rate (BER) of less than 10^{-9} in comparison to 69 DSF based OPCs. In addition, with the introduction of 100 SOA based OPCs, the system can withstand the fiber nonlinearity of up to 2.0 $W^{-1}km^{-1}$ for a 15,000 km transmission distance.

Keywords: polarization modulation (POLSK), optical transmission, optical phase conjugator, ultra-long haul communication, wavelength division multiplexing

Classification: Photonics devices, circuits, and systems

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DOI: 10.1587/elex.1.386
Received September 02, 2004
Accepted September 21, 2004
Published October 10, 2004

IEICE Electronics Express, Vol.1, No.13, 386–391

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1 Introduction

When updating the 10 Gbit/s optical transmission systems to 40 Gbit/s, the main limits are the chromatic dispersion, nonlinear effects, especially the interactions of dispersion and intra-channel nonlinearities. To achieve 40 Gbit/s transmission using the embedded fiber base, several possible modulation formats such as nonreturn-to-zero (NRZ), return-to-zero (RZ), and carrier-suppressed RZ (CS-RZ), have been employed [1, 2, 3] in the ultra dense wavelength division multiplexing (UDWDM) optical transmission systems. These systems are technologically very challenging and require an accurate design of transmitter, link, and receiver schemes depending on the spectral efficiency of the preferred modulation format. Performance comparison of the modulation formats such as NRZ, RZ, CS-RZ, duobinary, and differential phase-shift-keying (DPSK) in UDWDM has been reported by G. Basco *et al.* [4].

In this paper, we present optimized 40 Gbit/s of polarization modulation or POLarization Shift Keying (POLSK) [5] ultra-long haul transmission systems, where digital information is encoded in the state of polarization of the launched light, by using the optical phase conjugator (OPC). The main advantage of POLSK over other modulation formats is a constant envelope, thus demonstrating reduced sensitivity to self phase modulation (SPM) and

DOI: 10.1587/elex.1.386
Received September 02, 2004
Accepted September 21, 2004
Published October 10, 2004

cross phase modulation (XPM). Besides, POLSK also offers a 3 dB better sensitivity (for binary systems) in terms of peak power and the feasibility of bandwidth as well as power efficient multilevel systems [5].

2 Optical Link Model

POLSK transmission encodes information on a constellation of signal points in the space of the Stokes parameters. In general, each signal point corresponds to a given state of polarization and a given optical power. If only the polarization of the lightwave, not its power, is modulated, all the signal points lie on the Poincare sphere [5]. In this letter, we will restrict to constellation of equal power signal points and binary POLSK or 2-POLSK.

Fig. 1 depicts the block diagram of 2-POLSK system. In the transmitter module, a pseudo-random bit sequence (PRBS) generator is used as the source of information to be transmitted at a rate of 40 Gbit/s. The polarization driver converts the bit sequence into two electrical outputs (signals). These two output signals represent the relative phase between two linear polarization states and the power of the input signal between horizontal and vertical polarization. The role of the polarization modulator is to change the state of polarization (SOP) of the optical carrier from the laser based on the electrical signals from the 2-POLSK driver.

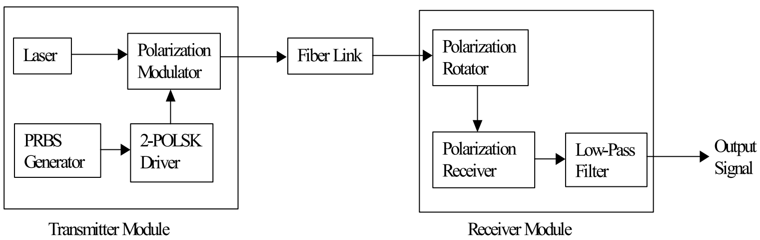

Fig. 1. Diagram of a 2-POLSK system.

At the receiver module, the incoming signal is first fed into a polarization rotator to change the SOP so that the 2-POLSK receiver could detect the signal. The detailed specifications of the 2-POLSK receiver could be referred to references [5] and [6]. The output of the 2-POLSK receiver is corrupted by high frequency harmonics that are introduced during the modulation. Thus, a post-detection filter – Bessel low-pass filter is used to extract the baseband signal.

The 2-POLSK is analyzed by using the commercial optical system simulation package RSOFT OptSim 4.0, which includes an accurate numerical solver for the two-polarization non-linear Schrödinger equation [7]. The laser source is from Fujitsu 1,550 nm multi-quantum well (MQW) distributed feedback (DFB) laser FLD5F10NP-A. Meanwhile, the polarization modulator from General Photonics Corp. is chosen (PPM-NC-7) in which the insertion loss is less than 0.1 dB and could easily modulate the operating wavelength from 1,200 nm to 1,620 nm.

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Received September 02, 2004
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For the fiber link, we used non-zero dispersion-shifted fiber with dispersion D = −1.0 ps/nm/km, compensated every 5 spans by a proper length of standard fiber (D = +17 ps/nm/km). The fiber polarization mode dispersion (PMD) was set to 0.1 ps/km$^{1/2}$. All other important fiber parameters were taken into account, including third order dispersion and stochastic birefringence that could be found in Corning® LEAF® optical fiber data sheet. We consider our system is periodically amplified in every 50 km by erbium-doped fiber amplifier (EDFA) with noise figure of 5 dB. The simulated EDFA is based on the Avanex's PureGain™ with the output power set at 7 dBm. For the receiver parameters, we used the 40 G PIN with HEMT IC pre-amplifier by Fujitsu (FRM5L442BZ). This receiver offers 40 GHz of 3 dB bandwidth and less than 0.5 dB of polarization dependant loss (PDL).

During the ultra-long haul transmission, the fiber loss is periodically compensated by EDFAs in order to maintain the signal power at a high level along the entire length of fiber. Hence, the dependence of the fiber refractive index on the optical power (Kerr effect) could no longer be neglected. When Kerr effect is not involved, the waveform distortion due to the group-velocity dispersion can be prevented by using the zero-dispersion fiber or compensated by the equalizer fiber [8]. However, the presence of the Kerr effect makes these methods less effective. In order to overcome both nonlinear and dispersive effects, mid-span spectral inversion (MSSI) has been identified as a very promising technique.

The performance of the 2-POLSK transmission systems is very much dependant on optimal placement of the OPC [9], which must be coherent with the MSSI theory, allowing perfect compensation of nonlinear effects, for example group-velocity dispersion and Kerr effect, and producing no perturbation power at all. Here, we have used the OPC placement method proposed by P. Minzioni *et al.* [10] to remove all in-line dispersion compensators, reducing span losses and system cost, assuming the normal dispersion region is used for transmission and the amplifier spacing is properly chosen. Both semiconductor optical amplifier (SOA) based OPC as well as dispersion shifted fiber (DSF) based OPC in the 40 Gbit/s POLSK systems are evaluated in the systems [11, 12].

3 Simulation Results and Discussions

Fig. 2 illustrates the logarithmic of bit error rate (BER) for a 10,000-km POLSK transmission systems versus the number of OPC deployed along a 10,000 km 40 Gbit/s 2-POLSK transmission system for both SOA and DSF based OPC. It is interesting to note that for the SOA based, only 100 OPCs need to be installed in order to achieve the BER of less than 10^{-22} compared with the DSF based OPCs where 128 OPCs are required to obtain the BER of 10^{-17}. Any additional of OPCs will not improve the BER of the system. Nevertheless, only 53 and 69 OPCs are needed to achieve BER $< 10^{-9}$, for SOA based and DSF based OPCs, respectively. This could be easily understood and proven in the experiment, which was carried out by S. Y. Set *et*

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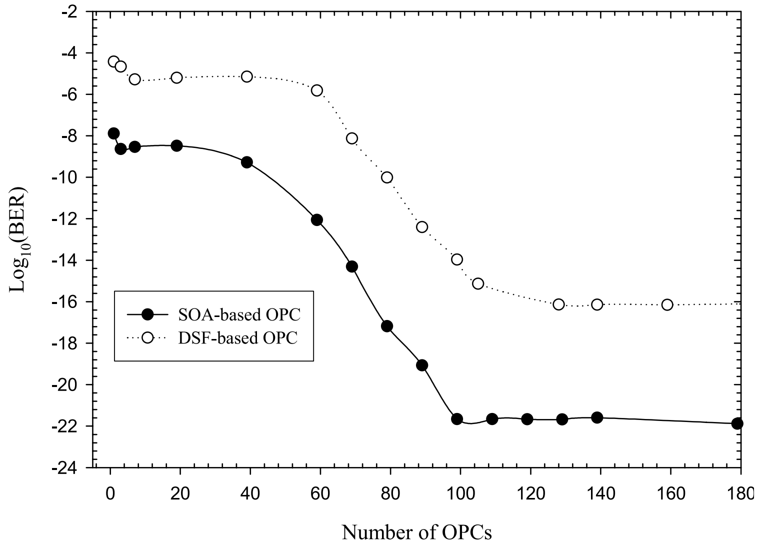

Fig. 2. The Log_{10} (BER) versus number of OPCs used along the 10,000 km 2-POLSK transmission systems for SOA based OPC and DSF based OPC.

al. [13].

When 100 SOA based OPCs are strategically installed in the 2-POLSK transmission system, it is noted that the system can achieve the maximum transmission distance of 15,000 km (BER $< 10^{-9}$) even though the fiber nonlinearity is increased from $\gamma = 1.5\,\text{W}^{-1}\text{km}^{-1}$ to $\gamma = 2.0\,\text{W}^{-1}\text{km}^{-1}$ as shown in Fig. 3 (a). However, the system starts to be distorted after 11,000 km for $\gamma = 2.3\,\text{W}^{-1}\text{km}^{-1}$.

The corresponding eye pattern diagrams for 15,000 km 2-POLSK transmission system when fiber nonlinearity, $\gamma = 1.5\,\text{W}^{-1}\text{km}^{-1}$ and $\gamma = 2.3\,\text{W}^{-1}\text{km}^{-1}$ are shown in Figs. 3 (b) and 3 (c), respectively, when 100 SOA based OPCs are installed. The obvious difference between the two eye pattern diagrams is that Fig. 3 (b) shows slower transition from the intensity level representing logic '0' to logic '1'. This distortion has narrowed the eye opening, resulting in an increase of BER. This phenomenon is mainly caused by the nonlinear effects of SPM and XPM. One of the ways to mitigate these unwanted effects is to use fibers with larger effective areas but this shall again incurred other undesirable effects like modal dispersion etc.

4 Conclusion

In this paper, we have investigated the feasibility of 40 Gbit/s 2-POLSK transmission systems using optical phase conjugators. The effects of both semiconductor optical amplifier (SOA) and dispersion shifted fiber (DSF) based OPCs on the 10,000 km system are investigated. It is found that only 53 SOA based OPCs are needed in order to achieve the bit-error-rate (BER) of less than 10^{-9} compared with 69 DSF based OPCs. In addition, with the introduction of 100 SOA based OPCs, the system can withstand the fiber nonlinearity of up to $2.0\,\text{W}^{-1}\text{km}^{-1}$ for a 15,000 km transmission distance.

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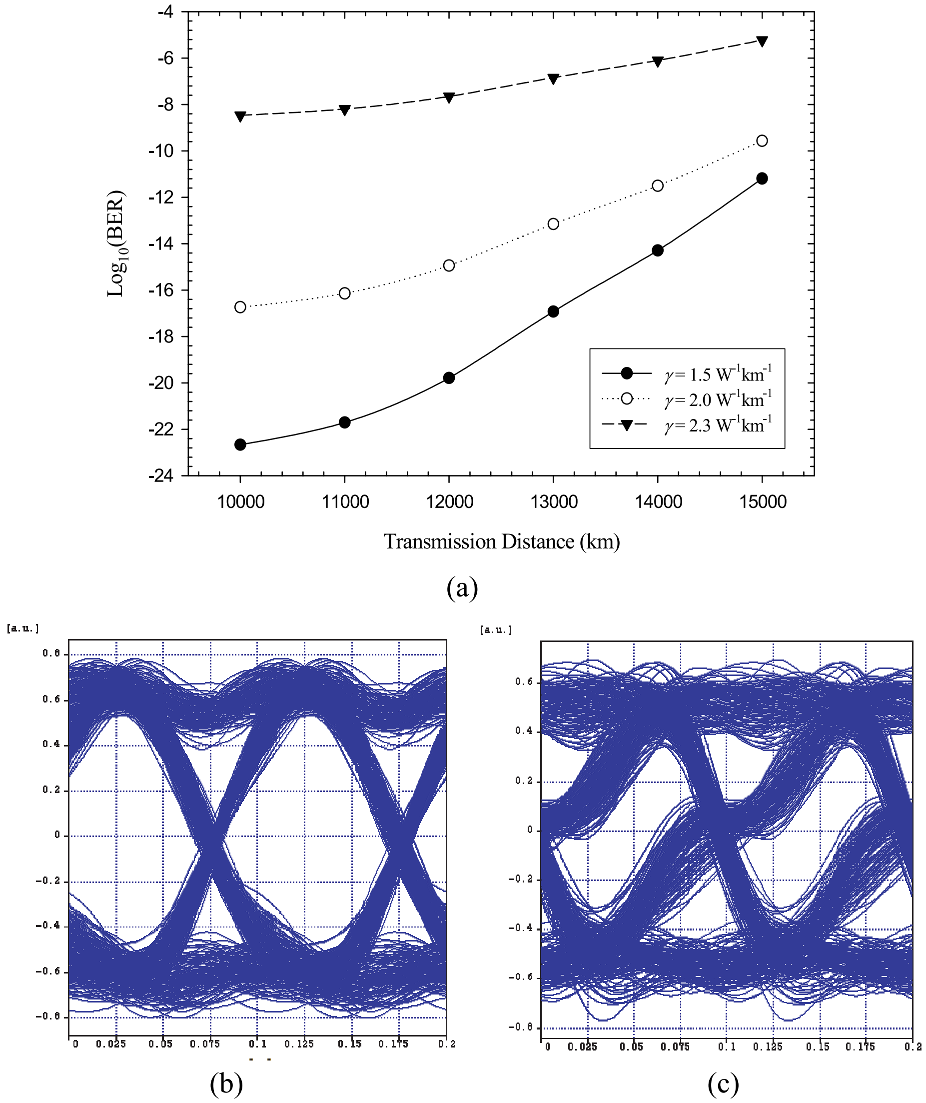

Fig. 3. (a) The $\mathrm{Log}_{10}\,(\mathrm{BER})$ versus transmission distance of 2-POLSK transmission system for different fiber nonlinearity when 100 SOA based OPCs are used. (b) The corresponding eye pattern for 15,000 km 2-POLSK when $\gamma = 1.5\,\mathrm{W}^{-1}\mathrm{km}^{-1}$ (c) $\gamma = 2.3\,\mathrm{W}^{-1}\mathrm{km}^{-1}$

Acknowledgments

This work was supported in part by the Malaysia Ministry of Science, Technology and Innovation (MOSTI) under Grant 09-99-01-0078 EA075. Special thanks to Fujitsu, Corning and RSOFT OptSim research team members for their assistance in providing the components parameters and results verifications.

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