ELectronics EXpress

IEICE Electronics Express, Vol.2, No.9, 305–310

Chromatic dispersion power penalties in orthogonal subcarrier—optical tandem single sideband systems

Hairul A. Abdul-Rashid[1a)], **Hean-Teik Chuah**[1], **Moncef B. Tayahi**[2], **Malik T. Al-Qdah**[1], **and Ruen-Chung Lee**[1]

[1] *Optical Communications and Networking Group,*
Center for Photonics Research, Innovation and Applications,
Faculty of Engineering, Multimedia University, Cyberjaya 63100, Malaysia
[2] *Department of Electrical Engineering, Mail Stop 260*
University of Nevada, Reno, NV 89557, USA
a) *hairul@mmu.edu.my*

Abstract: This paper deals with power penalties in Optical Tandem Single Sideband system using orthogonal subcarriers due to chromatic dispersion. The upper and lower sideband orthogonality is affected by chromatic dispersion. This phase imbalance causes degradation of quadrature demodulation performance. The effect is demonstrated by a mathematical model and verified by simulation results.

Keywords: chromatic dispersion, orthogonal subcarriers, optical tandem single sideband, subcarrier multiplexing

Classification: Photonics devices, circuits, and systems

References

[1] R. Gross and R. Olshansky, "Multichannel coherent FSK experiments using subcarrier multiplexing techniques," *J. Lightwave Technol.*, vol. 8, pp. 406–415, March 1990.
[2] G. H. Smith, D. Novak, and Z. Ahmed, "Technique for optical SSB generation to overcome dispersion penalties in fiber-radio systems," *Electron. Lett.*, vol. 33, no. 1, pp. 74–75, Jan. 1997.
[3] T. E. Darcie, "Subcarrier multiplexing for lightwave networks and video distribution systems," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 1240–1248, Sept. 1990.
[4] G. J. Meslener, "Chromatic Dispersion induced distortion of modulated monochromatic light employing direct detection," *IEEE J. Quantum Electron.*, vol. 20, no. 10, pp. 1208-1216, Oct. 1984.
[5] A. Narasimha, X. J. Meng, M. C. Wu, and E. Yablonovitch, "A 'tandem' single sideband fiber-optic system using a dual-electrode Mach-Zehnder modulator," *Proc. Conf. on Lasers and Electro-Optics (CLEO 2000)*, San Francisco, USA, CMR6, pp. 95–96, May 2000.
[6] A. Narasimha, X. J. Meng, C. F. Lam, M. C. Wu, and E. Yablonovitch, "Maximizing Spectral Utilization in WDM Systems by Microwave Domain Filtering of Tandem Single Sideband," *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 10, pp. 2042–2047, Oct. 2001.

DOI: 10.1587/elex.2.305
Received February 26, 2005
Accepted April 12, 2005
Published May 10, 2005

ELectronics EXpress
IEICE Electronics Express, Vol.2, No.9, 305–310

[7] Hairul A. Abdul-Rashid, Hean-Teik Chuah, Moncef B. Tayahi, Malik T. Al-Qdah, and Ruen-Chung Lee, "An orthogonal subcarrier based optical tandem single sideband system," *IEICE Electron. Express*, vol. 1, no. 16, pp. 490–494, Nov. 2004.
[8] Xinping Huang, "On Transmitter Gain/Phase Imbalance Compensation at Receiver," *IEEE Commun. Lett.*, vol. 4, no. 11, pp. 363–365, Nov. 2000.

1 Introduction

Subcarrier Multiplexed (SCM) systems [1] have received a considerable amount of interest in the last decade, mainly in areas such as radio-on-fiber systems and multi-channel video distribution [2, 3]. A significant advantage of optical SCM systems is that the RF components needed are more mature compared to their optical counterpart, for instance, the availability of a stable RF oscillator and the high resolution RF filters. SCM transmission systems however experience high dispersion penalty [4]. Optical single sideband (OSSB) modulation has been proposed to reduce chromatic dispersion related penalty [2]. Recently, an optical tandem single sideband (OTSSB) technique that enables transmission of different channels on each of the two sidebands, thus effectively doubling the bandwidth efficiency was proposed. Reflective fiber grating and optical image rejection mixer was proposed for detection of OTSSB signals [5, 6]. Recently, the authors reported a new way to transmit and receive in OTSSB system by using orthogonal subcarrier pairs [7]. In this technique, the OTSSB signal is directly detected using a PIN photodiode and further demodulated using quadrature demodulators. However, the upper and lower sideband orthogonality is affected by chromatic dispersion (CD), thus affecting quadrature demodulation performance [8].

In this letter, we demonstrate the effects of CD in OTSSB systems using orthogonal subcarrier pairs by a mathematical model. This model is verified by simulation results of transmission using different lengths of single mode fiber (SMF).

2 Mathematical Model

The optical carrier and single sideband modulation are generated using a dual-electrode Mach-Zehnder modulator (DE-MZM). A distributed feedback (DFB) laser with amplitude A and frequency f_c is externally modulated by a pair of orthogonal subcarrier with signal frequency f_m, amplitude V_1 and V_2. The orthogonal subcarrier pairs, denoted as $V_1 \cos \omega_m t$ and $V_2 \sin \omega_m t$, are applied to both the electrodes through two 90° hybrid couplers. The first arm of the DE-MZM is biased at V_{DC}, while the other arm is grounded. A DE-MZM with a switching voltage of V_π can be modeled as two optical phase-modulators in parallel with output signal $E_o(t)$. When the DE-MZM is biased at quadrature and both the modulating signal drives are small; $E_o(t)$

DOI: 10.1587/elex.2.305
Received February 26, 2005
Accepted April 12, 2005
Published May 10, 2005

IEICE Electronics Express, Vol.2, No.9, 305–310

can be expanded using the Bessel functions to

$$E_o(t) = \frac{A}{2}\begin{bmatrix} J_0(\varepsilon\pi)\cos(\omega_c t + \varphi_0) \\ -J_0(\gamma\pi)\sin(\omega_c t + \varphi_0) \\ -J_1(\gamma\pi)\cos\{(\omega_c - \omega_m)t + \varphi_1\} \\ -J_1(\gamma\pi)\cos\{(\omega_c + \omega_m)t + \varphi_2\} \\ -J_1(\varepsilon\pi)\cos\{(\omega_c - \omega_m)t + \varphi_1\} \\ +J_1(\varepsilon\pi)\cos\{(\omega_c + \omega_m)t + \varphi_2\} \end{bmatrix} \tag{1}$$

where $\omega_c = 2\pi f_c$, $\omega_m = 2\pi f_m$, $\gamma = (V_1 + V_2)/V_\pi$, $\varepsilon = (V_2 - V_1)/V_\pi$ and φ_n represents the phases of the different spectral components due to the CD of the fiber link. The phase of a single optical spectral component propagating through a fiber is $\varphi_n = \beta(\omega)z$ where $\beta(\omega)$ is the propagation constant and z is the distance traveled in the fiber. After expanding $\beta(\omega)$ in a Taylor series about ω_c and assuming the operating wavelength is not near the zero dispersion point and neglecting the constant phase, constant delay and higher order terms, we can re-write the phase as [4]

$$\varphi_n = \left(-z\lambda_c^2/4\pi c\right) D\,(\omega - \omega_c)^2 \tag{2}$$

where λ_c is the wavelength corresponding to the optical radial frequency ω_c. Equation (2) can be substituted into equation (1) and the added phase φ_1 and φ_2 can be represented as

$$\varphi_1 = \varphi_2 = \left(-z\lambda_c^2/4\pi c\right) D\omega_m^2 \tag{3}$$

When $E_o(t)$ is detected at the photodetector, the photocurrent can be written as

$$\begin{aligned} I(t) &= \Re \cdot LP\left\{|E_o(t)|^2\right\} \\ &= \frac{\Re \cdot A^2}{4}\begin{bmatrix} \frac{1}{2}\left\{J_0^2(\gamma\pi) + J_0^2(\varepsilon\pi)\right\} \\ +J_1^2(\gamma\pi) + J_1^2(\varepsilon\pi) \\ -J_0(\gamma\pi)\cdot J_1(\gamma\pi)\{2\sin(\varphi_1)\cos(\omega_m)t\} \\ -J_0(\varepsilon\pi)\cdot J_1(\gamma\pi)\{2\cos(\varphi_1)\cos(\omega_m)t\} \\ +J_0(\gamma\pi)\cdot J_1(\varepsilon\pi)\{2\cos(\varphi_1)\sin(\omega_m)t\} \\ -J_0(\varepsilon\pi)\cdot J_1(\varepsilon\pi)\{2\sin(\varphi_1)\sin(\omega_m)t\} \end{bmatrix} \end{aligned} \tag{4}$$

where $\Re$ is the responsivity of the photodetector, $LP\{\bullet\}$ operator denotes the low pass filter function of the photodetector. Equation (4) shows that the orthogonality of the subcarriers is disrupted by the added phase φ_1, which is dependent on CD, the subcarrier frequency f_m and the distance traveled z. The phase imbalance will affect the performance of the quadrature demodulation process [8].

3 Simulation Results

The proposed system is simulated for transmission of two 200 Mb/s baseband data channels A and B that modulate a pair of orthogonal subcarriers at frequency $f_m = 5.0$ GHz. The modulated orthogonal subcarrier pairs are

DOI: 10.1587/elex.2.305
Received February 26, 2005
Accepted April 12, 2005
Published May 10, 2005

then fed into a 90° hybrid coupler, producing a duplicate of the same signal differentiated by a 90° phase shift. These signals are used to externally modulate the CW laser using a dual-electrode Mach-Zehnder modulator (DE-MZM) as shown in the simulation setup in Fig. 1.

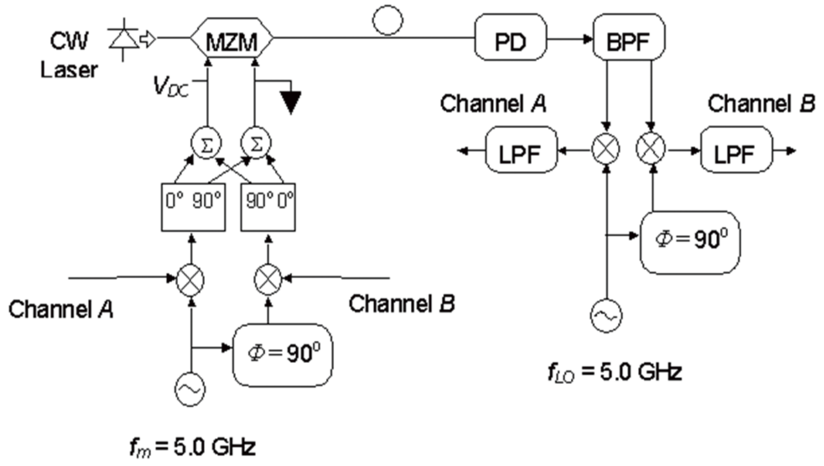

Fig. 1. Simulation setup of an Optical Tandem Single Sideband (OTSSB) system using orthogonal sub-carriers

The light source is a CW laser with 10 MHz linewidth and 0 dBm output power. The light from the CW laser is coupled into a dual-electrode Mach-Zehnder (DE-MZM) modulator that has a switching voltage V_π value of 5.0 V and biased at quadrature point. The two BPSK 200 Mb/s baseband data channels are generated by two pseudorandom generators clocked at 200 MHz with a $2^{20}-1$ pseudorandom bit sequence (PRBS). A hybrid 90° phase shifter is used to shift each of the modulated signals and the composite signal is used to drive the DE-MZ modulator as shown in Fig. 1. The DE-MZM is coupled to the receiver through a span of SMF with a dispersion coefficient of 16 ps/nm·km. At the receiver, the optical signal is detected using a PIN diode with a responsivity of 0.7. The channels A and B are demodulated using a quadrature demodulator. The output of the demodulator is shaped using a low pass filter with a cut-off frequency of 200 MHz.

The Bit Error Rate (BER) vs. Received Power (dBm) graphs of both channels A and B for three different lengths of SMF are plotted in Fig. 2 and Fig. 3 respectively. The eye diagrams of channels A and B shown as an inset in Fig. 2 and Fig. 3 respectively are for two different lengths of SMF; 10 KM (top) and 15 KM (bottom). The receiver sensitivity at BER of 10^{-9} for channel A after 10 KM is −39.8 dBm, after 15 KM is −39.5 dBm and after 20 KM is −39.2 dBm. The eye-opening for channel A after 10 KM is 3.14 dB and after 20 KM is 2.43 dB. The receiver sensitivity at BER of 10^{-9} for channel B after 10 KM is −39.5 dBm and −33.6 dBm after 15 KM. Transmission after 15 KM and 20 KM was limited to an error floor of 8.5×10^{-9} and 8.1×10^{-13} respectively. The eye-opening for channel B after 10 KM

DOI: 10.1587/elex.2.305
Received February 26, 2005
Accepted April 12, 2005
Published May 10, 2005

IEICE Electronics Express, Vol.2, No.9, 305–310

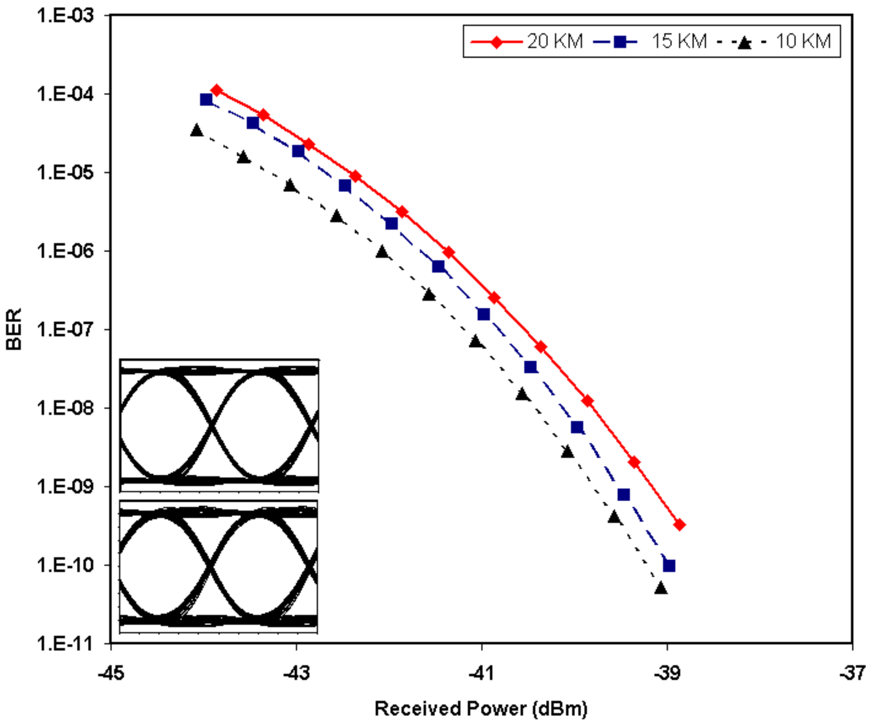

Fig. 2. Bit Error Rate vs. Received Power (dBm) for Channel A (in-phase) using different lengths of SMF. Inset: Eye diagram for different lengths of SMF; 10 KM [Top] and 15 KM [Bottom]

is 2.48 dB and after 15 KM is 1.86 dB

Channel A was demodulated using a local oscillator signal with radial frequency ω_m and phase adjusted to accommodate the added phase φ_1 in the received signal. As a result, the demodulated signal did not suffer from any interference from the orthogonal Channel B. However, the demodulated signal's amplitude is now scaled by a factor $\cos\varphi_1$, where φ_1 is the added phase due to CD. Hence, the power penalty shown in Fig. 2 is caused by not only fiber loss, but also CD in the SMF.

The orthogonal Channel B was demodulated using the same local oscillator signal with radial frequency ω_m but with a 90° phase-shift. The demodulated signal is distorted by CD dependant interferences from the in-phase Channel A. However, the demodulated signal's amplitude is not scaled by any factor. Hence, the severe power penalty and error floor shown in Fig. 3 is caused by both fiber loss and interferences from Channel A, which is dependent on CD in the SMF.

4 Conclusion

We have analyzed the power penalty due to CD of an OTSSB system using orthogonal subcarrier pairs. We showed, using a mathematical model, that the dispersion penalty was dependent on subcarrier frequency, dispersion and distance. We verified the mathematical model through a simulation exercise, which show the power penalties for the transmission of two 200 Mb/s with

DOI: 10.1587/elex.2.305
Received February 26, 2005
Accepted April 12, 2005
Published May 10, 2005

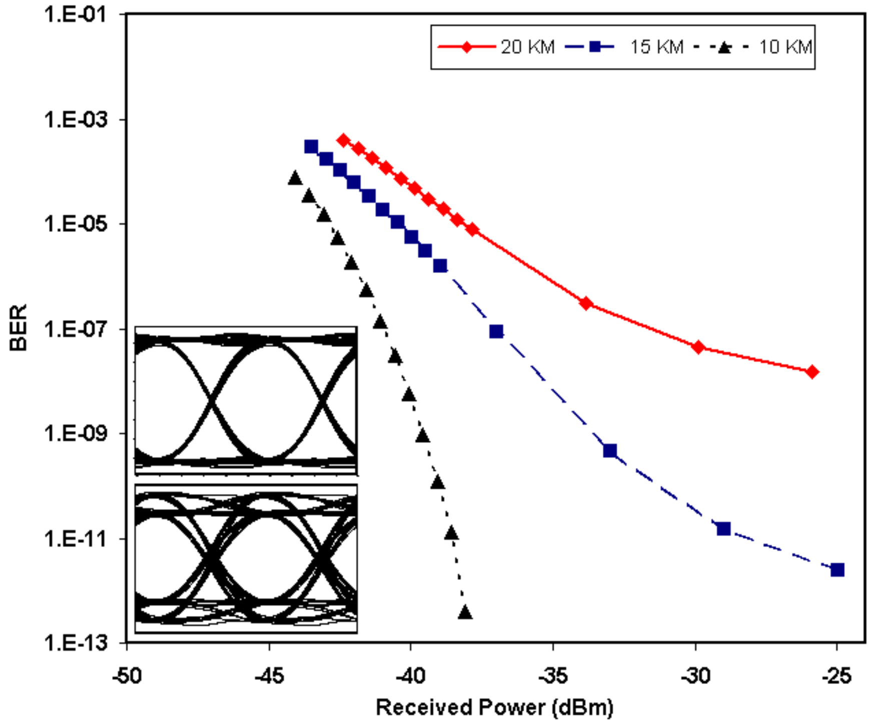

Fig. 3. Bit Error Rate vs. Received Power (dBm) for Channel B (quadrature) using different lengths of SMF. Inset: Eye diagram for different lengths of SMF; 10 KM [Top] and 15 KM [Bottom]

different lengths of SMF. The power penalties reveal that the performance of OTSSB system using orthogonal subcarrier pairs can be limited due to CD and compensation techniques need to be employed to improve the performance.

ELectronics EXpress

DOI: 10.1587/elex.2.305
Received February 26, 2005
Accepted April 12, 2005
Published May 10, 2005