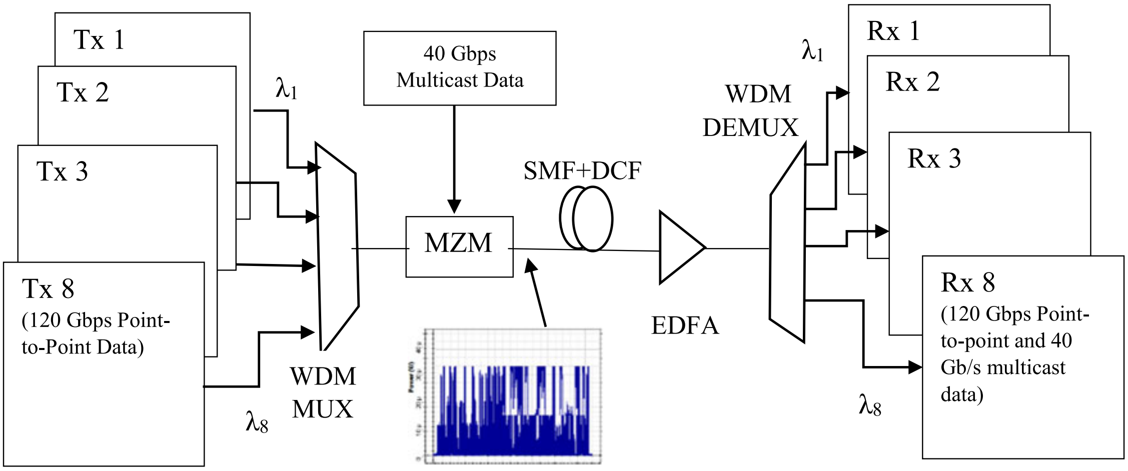
IEEE Photonics Journal
An IEEE Photonics Society Publication

Limitations on Hybrid WDM/OTDM Multicast Overlay System Imposed by Nonlinear Polarization Effect and its Mitigation

Volume 9, Number 5, October 2017

Sukhbir Singh
Surinder Singh



DOI: 10.1109/JPHOT.2017.2750483

Limitations on Hybrid WDM/OTDM Multicast Overlay System Imposed by Nonlinear Polarization Effect and its Mitigation

Sukhbir Singh and Surinder Singh

Department of Electronics and Communication Engineering, Sant Longowal Institute of
Engineering and Technology, Longowal 148106, India

DOI:10.1109/JPHOT.2017.2750483

Manuscript received April 10, 2017; revised August 30, 2017; accepted August 31, 2017. Date of current version October 5, 2017. This work was supported by the AICTE, New Delhi under Research Projects 20/AICTE/RIFD/RPS (POLICY-1)60/2013-14. Corresponding author: Surinder Singh (e-mail: surinder_sodhi@rediffmail.com).

Abstract: This paper investigates the nonlinear polarization effect of 120-Gbps polarization and subcarrier multiplexed unicast signal and 40-Gbps multicast signal on transmission performance of hybrid WDM/OTDM multicast overlay system. The interaction between Kerr nonlinearity and polarization mode dispersion (PMD) induced nonlinear cross polarization modulation (XPolM) effect can significant limits the transmission performance of hybrid WDM/OTDM multicast overlay system. The effect of signal input power, extinction ratio, PMD, and differential group delay is studied in multicast enable and disable mode. Also, a mitigation technique of nonlinear polarization effect is introduced by use of group delay compensator, judicious addition of some PMD, and inline pre-DCF in the transmission channel. It is also found that the amplitude to phase interaction between multicast and unicast signal transmission can be suppressed by controlling the loss of orthogonality.

Index Terms: Hybrid WDM/OTDM, orthogonal modulation format, cross polarization modulation (XPolM), extinction ratio, polarization mode dispersion (PMD), differential group delay (DGD), DCF, Q-factor.

1. Introduction

Recently, high speed long-haul optical fiber communication networks have experienced tremendous growth with revival of advanced optical techniques such as coherent detection technology, orthogonal modulation formats, hybrid multiplexing, hybrid amplification etc. Advanced optical modulation techniques are one of these to achieve such high data rate in limited available channel bandwidth [1]–[3]. Polarization division multiplexed (PDM) based orthogonal modulation format such as DRZ/DPSK [4], DRZ/DQPSK/PolSK [5], PDM-RZ-QPSK) [6], polarization and subcarrier multiplexed signal [7] etc. are promising modulation techniques used now-a-day having double transmission capacity and high spectral efficiency as compared to conventional modulation techniques. As well known in coherent PDM technique, two or more optical signals having orthogonal states of polarization (SOP) are transmitted at same wavelength and at receiver side, these orthogonally modulated signals need to be demultiplexed in respect of states of polarization (SOP) which are same as transmitted [8]–[10].

Orthogonal modulated signals are vulnerable to polarization effect such as polarization mode dispersion (PMD) arises due to birefringence of optical fiber and components and polarization dependent loss (PDL) occurred due to polarization dependence of isolators and couplers. PMD and PDL are also responsible for polarization fluctuation of orthogonal modulated signal and leads to performance degradation of high speed optical fiber transmission system. Also, Coherent polarization-diversity receivers utilized to increase system capacity without any extra hardware requirement at the receiver but such receivers are polarization sensitive and nonlinear polarization thus directly affect the system performance and becomes a key issue to be mitigate [11]–[13].

Various researchers have proposed numerous method to reduce nonlinear polarization effects in optical communication system. Casillas *et al.* [14] reported the linear polarization insensitive optical phase modulation detection by using two wave mixing in single mode polarization maintaining Er-doped fiber (EDF) for coherent optical communication at 1492 nm and achieved polarization drift below 100 Hz. Zhang *et al.* [15] have analyzed and demonstrated the all optical sampling technique which was based on nonlinear polarization rotation in semiconductor optical amplifier (SOA). Harmonic distortion occurred due to nonlinear essence of polarization rotation were overcome by polynomial transfer function method to compromise conversion efficiency of 1.35 and harmonic distortion of 2.01%. Xie *et al.* [16] analyzed the effect of state of polarization (SOP) of control pulse and 100 Gbps OTDM data signal on the FWM of a SOA which also limit the BER performance and optical time demultiplexing. They have achieved the best BER performance at $\theta = 0^\circ$ and maximum BER degradation at $\theta = 75^\circ$. Habib *et al.* [17] represented a modified rectangular structure based dispersion compensating fiber which maintain single polarization throughout the channel and ensure the high birefringence and negative dispersion -288 to -550 ps/(nm.km) for S, C band high bit transmission networks. Zhou *et al.* [18] presented an approach to reduce crosstalk between polarization multiplexed signals using polarization diversity pump FWM scheme. Due to FWM effect in SOA, two single polarization conversions have been performed which reduce crosstalk to great extent than conventional techniques.

This paper investigates the nonlinear polarization effect of 120 Gbps polarization and subcarrier multiplexed unicast signal and 40 Gbps DPSK multicast signal on the performance of hybrid WDM/OTDM multicast overlay system in respect of multicast enable and disable mode. The impact of input power, extinction ratio, PMD and DGD on the performance of hybrid WDM-OTDM system in terms of output power, Q-factor and output SOP has been analyzed and also give approach to mitigate these nonlinear polarization effect. The amplitude to phase interaction between the multicast and unicast signal due to birefringence of optical fiber and components also studied. The main finding of this paper is that nonlinear polarization can limits the average performance, both in single channel and hybrid WDM-OTDM transmission. Rest of paper is organized as follow. In Section 2, architectural setup of hybrid WDM/OTDM multicast overlay system and nonlinear polarization effect induced by orthogonal modulation has been shown. Section 3 presents the results that quantify the contribution of nonlinear polarization effect of 120 Gbps polarization and subcarrier multiplexed unicast signal and 40 Gbps multicast signal on performance limitation of hybrid system and their mitigation. Finally, the main conclusions have been made in Section 4.

2. Architectural Setup of Hybrid WDM/OTDM Multicast Overlay System to Evaluate the Effect of Nonlinear Polarization

The architectural setup of hybrid WDM/OTDM multicast overlay system is illustrated in Fig. 1. The 120 Gbps polarization and subcarrier multiplexed unicast signals and 40 Gbps multicast signal has been employed in hybrid WDM/OTDM system. Both polarization and phase of optical signal are utilized to carry the user‘s information for increase the spectral efficiency and system capacity. The detail of generation and detection of 120 Gbps polarization and subcarrier multiplexed signal is given in [7]. For simplicity, wavelength signal of 193.1 THz being used to evaluate the performance of WDM-OTDM multicast overlay system in presence of nonlinear polarization effect. As shown in Fig. 1, the designed hybrid system having eight (λ_1 to λ_8) 120 Gbps polarization and subcarrier multiplexed point to point data signal transmitters at channel spacing of

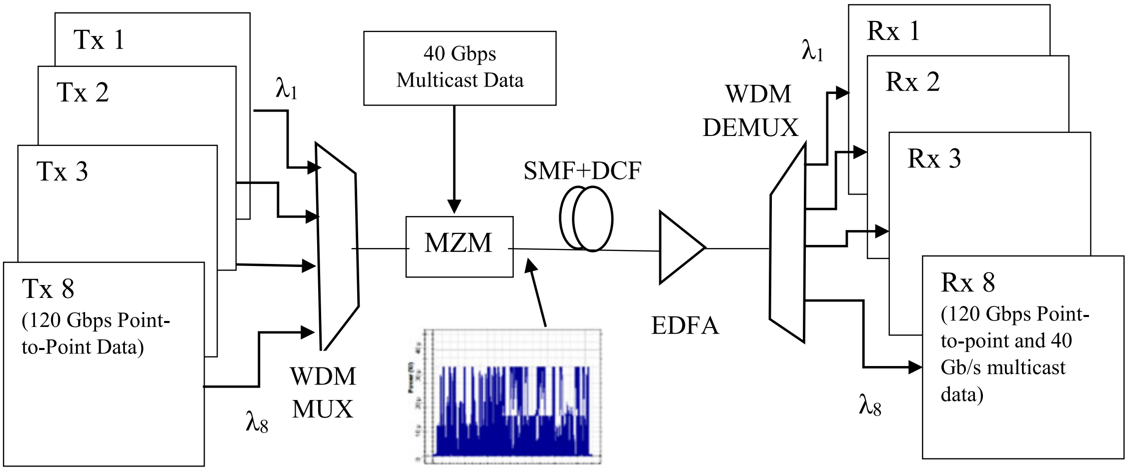


Fig. 1. Architecture of WDM-OTDM optical multicast overlay system employing 120 Gb/s point to point data and 40 Gb/s Multicast data [7].

TABLE 1

Different Parameters of SMF, DCF Consider for Design Hybrid WDM-OTDM Optical Multicast Overlay System

Fiber type	Fiber length (km)	Attenuation (dB/km)	Dispersion (ps/nm/km)	Dispersion Slope (ps/nm^2/km)	Effective Area (μm^2)	Differential Group Delay (ps/km)
SMF	40	0.2	17	0.075	70	0.2
DCF	8	0.5	−85	−0.3	22	0.2

TABLE 2

Parameter of EDFA Gain Amplifier Consider for Demonstration of Hybrid WDM-OTDM Optical Multicast Overlay System

Amplifier Type	Gain (dB)	Noise Figure (dB)	Noise Center Frequency (THz)	Noise Bandwidth (THz)
EDFA (Gain Control)	20	4	193.4	13

100 GHz and one 40 Gbps DPSK multicast data transmitter. Adequate time slots are allocated of $\tau_1 = 0\text{s}$, $\tau_2 = 1/(\text{Bitrate})*1/4$ ns, $\tau_3 = 1/(\text{Bitrate})*2/4$ ns and $\tau_4 = 1/(\text{Bitrate})*3/4$ ns respectively in order to avoid collision between subcarrier DQPSK and PolSK signal and proper orthogonality has been achieved by use of polarization controller (PC). Mach–Zehnder intensity modulator (IM) is used for superimposing the multicast data onto the multiplexed unicast signals. At the output of Mach–Zehnder intensity modulator (MZIM), 120 × 8 Gbps + 40 Gbps orthogonally modulated signals are detected and further connected to optical channel. The parameters of SMF+DCF and EDFA are shown in Tables 1 and 2 [19]–[26].

In fact, single mode fiber can support the finite number of orthogonally polarized modes and especially two modes in same spatial distribution [27[, [28]. When eight orthogonally modulated signals (λ_1 to λ_8) are passing through optical fiber and various optical components such as isolator, couplers, polarization controller etc. amplitude, phase or polarization of modulated signal will change with time. In single mode fiber, due to non-cylindrical symmetry of core, anisotropic stress on fiber, Chromatic dispersion and birefringence (both linear and nonlinear) will degenerate the polarized modes nx and ny of orthogonal modulated signals. Any fiber has two principle axes (i) slow axes and (ii) fast axes along which fiber maintain the state of polarization [27], [28]. When $nx > ny$, nx and ny are mode indices along the slow and fast axes then state of polarization will change along the fiber beat length $L_B = \lambda/B_m$ whether linear to elliptical or elliptical to linear.

The polarized optical beam launched into optical fiber can be expressed by (1) [27, 29,30]

$$E(r,t) = F(x,y)\left[\hat{x}A_x(z,t)e^{i\beta_x z} + \hat{y}A_y(z,t)e^{i\beta_y z}\right]e^{-i\omega_0 t} \tag{1}$$

and nonlinear contributions $\triangle n_x$ and $\triangle n_y$ can be given by (2) and (3) [27]

$$\Delta n_x = n_2\left(|A_x|^2 + \frac{2}{3}|A_y|^2\right) \tag{2}$$

$$\Delta n_y = n_2\left(|A_y|^2 + \frac{2}{3}|A_x|^2\right) \tag{3}$$

where, n_2 is the nonlinear parameter given by (4)

$$n_2 = \frac{3}{8n}\mathrm{Re}(\chi^{(3)}_{xxxx}) \tag{4}$$

The nonlinear contributions $\triangle n_x$ and $\triangle n_y$ are produce nonlinear birefringence. The magnitude of induced birefringence is dependent on intensity and state of polarization of CW light signals. Hence, nonlinear birefringence manifests the polarization ellipse rotation. The change in SOP due to nonlinear polarization leads to time dependent nonlinear scattering and causes SOP to change at speed of symbol rate. The phase difference exerted by two different polarized component is given by (5) and (6) [27]

$$\phi_x = \gamma\left(|A_x|^2 + \frac{2}{3}|A_y|^2\right)L_{eff} \tag{5}$$

$$\phi_y = \gamma\left(|A_y|^2 + \frac{2}{3}|A_x|^2\right)L_{eff} \tag{6}$$

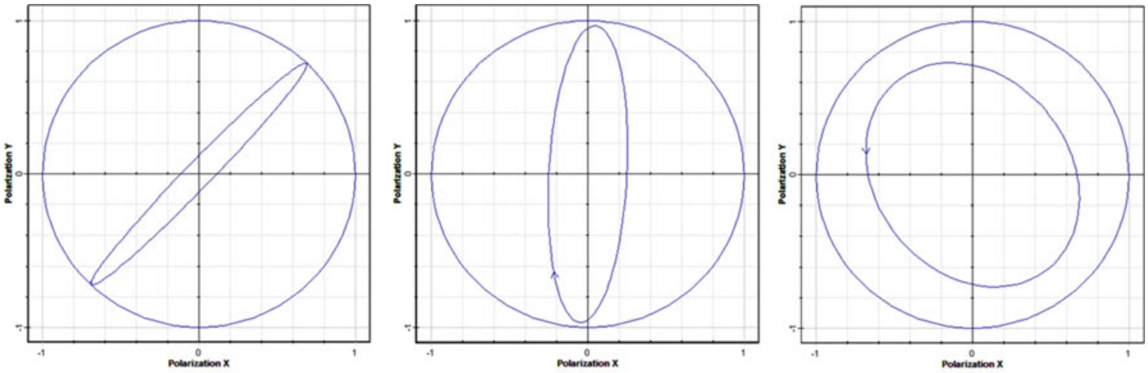
Due to finite relative phase difference between two polarizations component state of polarization is rotate as given by (7)

$$\triangle\phi_{NL} = \frac{1}{2}\gamma L_{eff}\left(|A_x|^2 - |A_y|^2\right) \tag{7}$$

Fig. 2 shows the SOP exerted by 193.1 THz orthogonally modulated signal at different stages of hybrid system. From Fig. 2 (b) and (c), amplitude to phase crosstalk between unicast and multicast signal, fiber CD and birefringence causes nonlinear polarization scattering which originate rotation in SOP of transmitted signal with time [31], [32]. The time dependent SOPs of orthogonal modulated signals and walk off between unicast and multicast signal will increases the nonlinear polarization scattering and limit the system performance. Received optical timing diagram are shown in Fig. 3 which are largely affected by nonlinear polarization scattering.

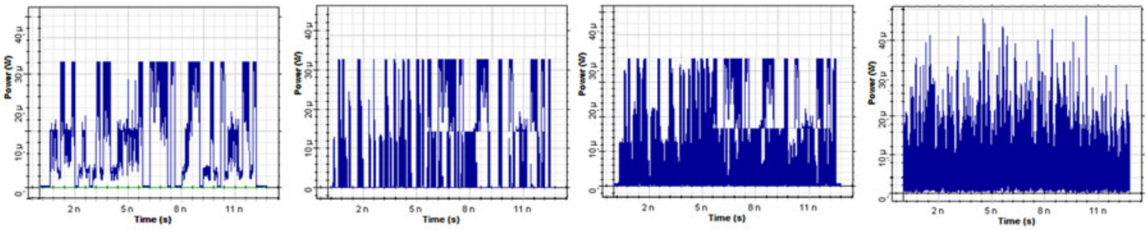
3. Performance Analysis of Hybrid WDM/OTDM Multicast Overlay System in Presence of Nonlinear Polarization and its Mitigation

To investigate the effect of nonlinear polarization on performance of hybrid WDM/OTDM multicast overlay system, eight orthogonally modulated signals at polarization angle of 45° each are



(a) (b) (c)

Fig. 2. Received SOPs of transmitted 193.1 THz orthogonal modulated signal at (a) output of point to point transmitter with SOP of 45° (b) output of Mach-Zehnder intensity modulator with SOP of 87.08° (c) output of optical channel with SOP $-54.98°$.



(a) (b) (c) (d)

Fig. 3. Received timing diagrams of transmitted signal at (a) output of transmitter (b) output of WDM-MUX (c) output of intensity modulator where multicast data is superimposed (d) optical channel.

transmitted over 100 km span of SMF+ inline DCF and EDFA amplification in C-band. In Fig. 4, orthogonally modulated signals are attaining the different SOP at different launched power. The attained SOP is entirely different from transmitted one and become difficult to recover the orthogonally modulated signals. When high power wavelength signals are transmitted through optical fiber or nonlinear components, nonlinear phase shift is induced and reflected indices for parallel and perpendicular components are varied due to birefringence. This phase difference manifests the change in state of polarization. The linear and nonlinear phase shift can be expressed by (8) and (9) [27].

$$\triangle\phi = (2\pi/\lambda)(\tilde{n}_x - \tilde{n}_y)L \tag{8}$$

$$\triangle\phi_{NL} = \gamma L_{eff}(1 - B)(P_x - P_y) \tag{9}$$

where $\tilde{n}_x$ and $\tilde{n}_y$ are polarization components, L is length of optical fiber, $\gamma$is nonlinear coefficient, L_{eff} is nonlinear effective length and P_x, P_y power related with polarization components.

The corresponding refractive index change $\triangle n_x$, $\triangle n_y$ and Kerr coefficient (n_{2B}) are given by (10)–(12) [27]–[29]

$$\triangle n_x = 2n_2|E_s|^2 \tag{10}$$

$$\triangle n_y = 2n_2 b|E_s|^2 \tag{11}$$

where $b = \chi^{(3)}_{xxyy} \,/\, \chi^{(3)}_{xxxx}$

$$n_{2B} = 2n_2(1 - b) \tag{12}$$

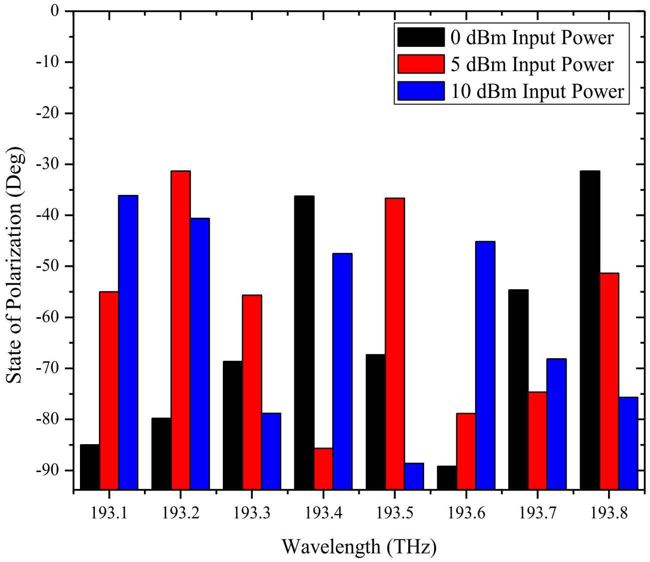


Fig. 4. State of polarization (SOP) exerted by different transmitted wavelength signals at output of optical channel for input power level of 0 dBm, 5 dBm and 10 dBm respectively (transmitted signals at polarization angle of 45°).

Condition to achieve maximum signal power transmission for complete compensation and π nonlinear phase shift is given below

$$P_s = \lambda A_{eff}/(2n_{2B}L_{eff}) \tag{13}$$

As from Fig. 4, with increase in the launched power nonlinear polarization effect of optical channel on SOP of transmitted signal is more because power dependency of optical nonlinearities and polarization division multiplexing makes dispersion management worst. Also, amplitude to phase crosstalk between unicast signal and multicast signal is another factor or nonlinear polarization effect.

There are main three approaches to mitigate the fluctuation of state of polarization (SOP) exertion due to fiber birefringence or PMD (i) Passive mitigation techniques including advanced robust modulation techniques and distributed polarization scrambling (ii) Electronics PMD compensation consisting maximum likelihood sequence estimation (MLSE), Decision feedback equalizer and (iii) Optical PMD compensation. Out of these optical PMD compensation is most effective for optical coherent system or direct detection system. In this investigation, we have considered modified SMF + pre-DCF parameters to suppress the nonlinear polarization effect. Modified parameters of SMF and pre-DCF are given in Table 3. In Fig. 1, the spectral efficient optical orthogonal modulated signal transmitter having time dependent SOPs and small walk-off between unicast and multicast signal has been observed. Spectral efficiency orthogonal modulation itself suppress the nonlinear polarization but fiber birefringence affects the data dependent SOPs of transmitted signals. So, to mitigate this effect, inline pre-DCF is used with dispersion of −180 ps/nm/km, nonlinear coefficient 1.17 $(\text{km}\cdot\text{W})^{-1}$ and 0.5 dB/km attenuation for 100 km transmission distance. In the dispersion management, the induced Chromatic dispersion in first will be compensated in second span by DCF and net residual dispersion after transmission can be further compensated in electrical domain by using digital signal processing (DSP). The system without DCF has more dominant effect of crosstalk due to XPM and peak power of polarized signals is much smaller as compared to single polarized signal. while utilized the pre-DCF with optimum dispersion value of −180 ps/nm/km, the GVD induced pulse broadening, CD and linewidth enhancement factor β_2 is limited. Pre-compensation further suppress the induced inter-channel crosstalk due to sideband overlapping of subcarrier and polarization multiplexed signals by limit the chirp induced during

TABLE 3
Modified Parameters of SMF, Pre-DCF Considered for Suppressing Effect of Nonlinear Polarization

Fiber type	Fiber length (km)	Attenuation (dB/km)	Dispersion (ps/nm/km)	Chromatic Dispersion (ps/nm·km)	Effective Area (μm^2)	Differential Group Delay (ps/km)	Nonlinear coefficient coefficient
SMF	40	0.21	17	17.5	70	0.2	2.36
DCF	8	0.5	−180	−0.3	22	1.6	1.17

modulation. Equation (14) clearly shows the pre-compensation for transmission system using optical orthogonal modulated signals imposed by the intrachannel nonlinear effects [33].

$$C_{pre} = \frac{-D}{\alpha} \ln\left[\frac{2}{1 + \exp(-\alpha \cdot L)}\right] \tag{14}$$

where D is dispersion, α is attenuation and L is attenuation of single mode fiber.

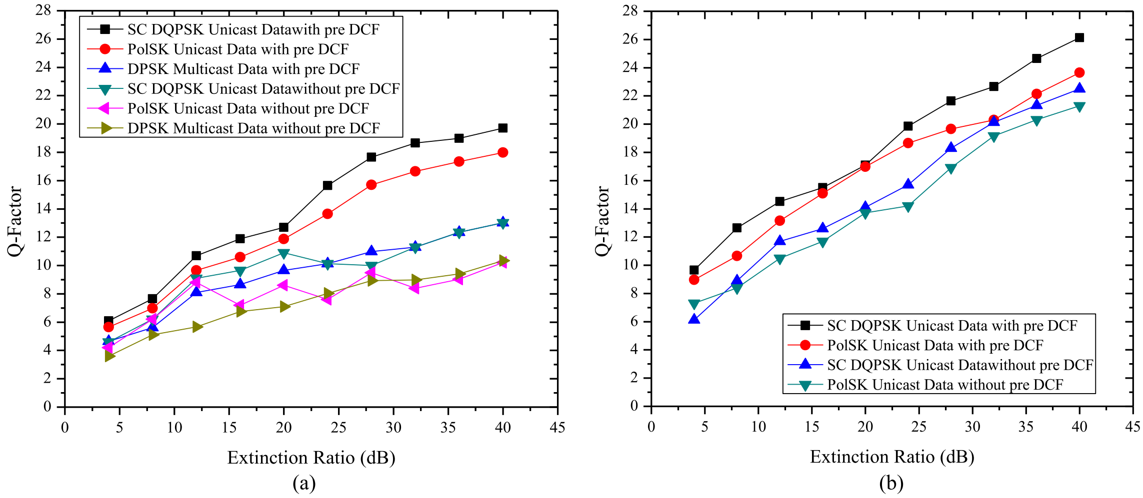
To evaluate the effect of extinction ratio (ER) on the Q-factor performance of system for with and without pre-DCF, ER is varied from 4 dB to 40 dB. The significant intensity distortions are induced due to residual dispersion and intra-channel nonlinear effects, when no pre-compensation is used. Intensity distortion occurred due to XPM and FWM effect in SMF. Due to XPM modulation, timing jitter of symbol '1' reaches at its maximum and cannot be separated by symbol rate. Due to FWM effect, FWM pulses are surrounded by '1' where position occupied by symbol '0'. However, by using pre-compensation, significant reduction in timing jitter and compensated intensity distortions. Hence, transmitted signals with a specific ER is directly proportional to nonlinear phase shift and given by (15).

$$\phi_{NL} = N \cdot P(0) \cdot \gamma L_{eff} \tag{15}$$

where N is number of channels, $P(0)$ is input signal power, γ is nonlinear coefficient and L_{eff} is the effective nonlinear length of SMF which is given by

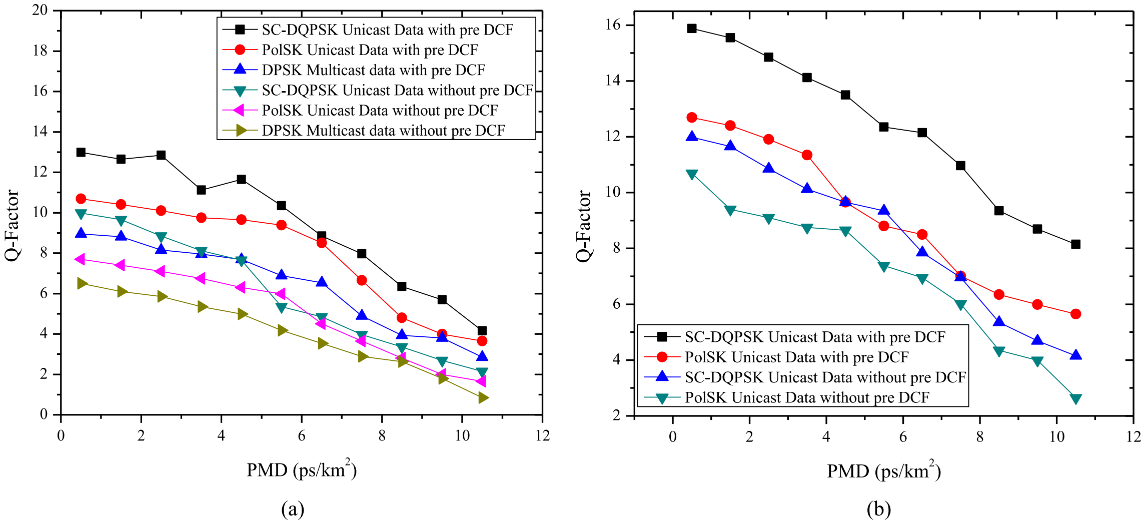
$$L_{eff} = \frac{1 - \exp(-\alpha L)}{\alpha} \tag{16}$$

Fig. 5(a) and (b) clearly shows the Q-factor performance of hybrid system before and after pre-compensation in multicast enable and disable mode at different values of extinction ratio of subcarrier DQPSK. The minimum value of ER is set to 9.13 dB, 8.2 dB and 16.9 dB for the detection of unicast subcarrier DQPSK data, unicast PolSK data and multicast DPSK data respectively when pre DCF is used. In Fig. 5(a), the effect of nonlinear polarization is higher when no inline pre-optical dispersion compensation is used hence fluctuation in Q-factor of transmitted signals. Also, inter-symbol interference between 120 Gbps polarization and subcarrier multiplexed unicast data and 40 Gbps multicast data significantly limits the quality of signals. For PolSK data without pre DCF, it is slightly lower extinction ratio than SC-DQPSK data because XPolM induced nonlinear polarization scattering. When pre-compensation is used, the Q-Factor and extinction is restored and improved by factor of 2. From Fig. 5(b), in multicast disable mode crosstalk between unicast and multicast signal is eliminated and Q-factor performance considerably improved as compare with multicast enable mode. While disable the multicast operation, Q-factor performance increase by factor 2 as compared to when multicast is enable without pre DCF. While use of pre DCF, unicast



(a) (b)

Fig. 5. Graphical representation between extinction ratio of subcarrier DQPSK and Q-Factor when (a) multicast operation in enable with and without DCF (b) multicast operation in disable with and without DCF (at channel no. 1).



(a) (b)

Fig. 6. Graphical representation between polarization mode dispersion (ps/km^2) and Q-Factor when (a) multicast operation in enable with and without DCF (b) multicast operation in disable with and without DCF (at channel no. 1 for extinction ratio 6.39 dB and input power 5 dBm).

signals present the high extinction ratio and minimum required ERs of DQPSK are 2.65 dB and 2.15 dB for detection of unicast subcarrier DQPSK data and unicast PolSK data respectively.

Fig. 6(a) and (b) shows the Q-factor penalty induced by polarization mode dispersion (PMD) in hybrid WDM/OTDM multicast overlay system in multicast enable and disable mode. Eight orthogonally modulated signals are transmitted 100 GHz apart from each other and it will ensure the inter-channel crosstalk due to nonlinear polarization and interaction between unicast and multicast signals. For 120 Gbps polarization and subcarrier multiplexed data, performance limited not by XPM but by XPolM which causes nonlinear polarization scattering between adjacent orthogonal signals when no pre-compensation in used. Nonlinear scattering will fluctuate the exertion state of polarization of each polarized signal. Also, PMD causes of pulse broadening and depolarization of transmitted signals through fiber. Due to depolarization of signal, crosstalk is induced between polarized signal which causes larger penalties, loss of orthogonality between orthogonal modulated

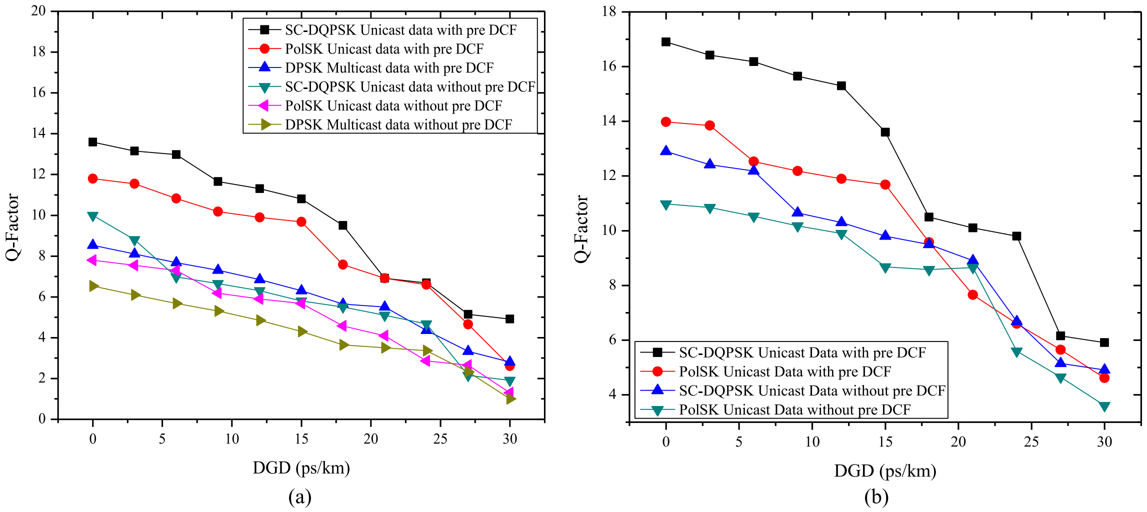


Fig. 7. Graphical representation between differential group delay (ps/km) and Q-Factor when (a) multicast operation in enable with and without DCF (b) multicast operation in disable with and without DCF (at channel no. 1 for extinction ratio 6.39 dB and input power 5 dBm).

signals, OSNR imbalanced between polarized signals. These penalties are much larger as comparable to pulse broadening of orthogonal modulated signals. By introducing the pre-compensation along with polarization controller or polarization scrambler, depolarization of signal due to PMD can be significant compensated. As from Fig. 6(a), Q-factor performance degraded at higher value of PMD with or without pre-DCF. As comparable without pre-DCF, use of inline pre-DCF improves the Q-factor performance by factor of ∼3. PolSK unicast data signal is more affected by XPolM than SC-DQPSK and this XPolM can be further mitigate by PGD inline compensator in the transmission link. Fig. 6(b) indicates the Q-factor performance of hybrid system in multicast disable mode. Here, dominant effect of PMD is observed at higher value which increase the Q-factor penalty. But as comparison between with and without pre-DCF compensation, pre-DCF improve the system performance.

Fig. 7(a) and (b) shows the Q-factor performance limitation at various values of differential group delay (DGD) in multicast enable and disable mode. The transmitted data dependent SOP signals are more sophisticated to PMD and induced inter-channel XPolM depolarized the data signal of each transmitter. Higher value of DGD causes large PMD-induced pulse broadening for 120 Gbps polarization and subcarrier multiplexed signal and 40 Gbps multicast signal. As well know, Q-factor penalty is proportional to DGD [13] and timing jitter induced by individual bits of data dependent SOP signals limits the Q-factor performance, when no pre-compensation is used. As from Fig. 7(a), it is clear that by use of pre-DCF, PMD-induced pulse broadening resists and improve the system performance by factor of ∼3.5 in multicast enable mode. System performance degraded above DGD $= 2\,\text{ps/km}^2$. Also in Fig. 7(b), it can be observed that pre-DCF can suppress the nonlinear polarization and improve the Q-factor by ∼4 in multicast disable mode.

As from Fig. 8, the smaller difference between 120 Gbps polarization and subcarrier multiplexed system with and without pre-DCF has been observed on degree of polarization (SOP) of 193.1 THz wavelength signal. It is also indicate that degree of polarization (DOP) of orthogonal modulated signal decrease more rapidly at higher level of input power with use of pre-DCF than without pre-DCF. This is happen due depolarization of signal by XPolM and fiber birefringence at higher power. So, to tradeoff this, optimum input power level of 5 dBm has been considered for the evaluation. Also from Figs. (6) and (7), inter-channel crosstalk induced by XPM is more than XPolM and dominant effect of XPM can be eliminated by using pre-compensation techniques to increase the improve Q-factor performance.

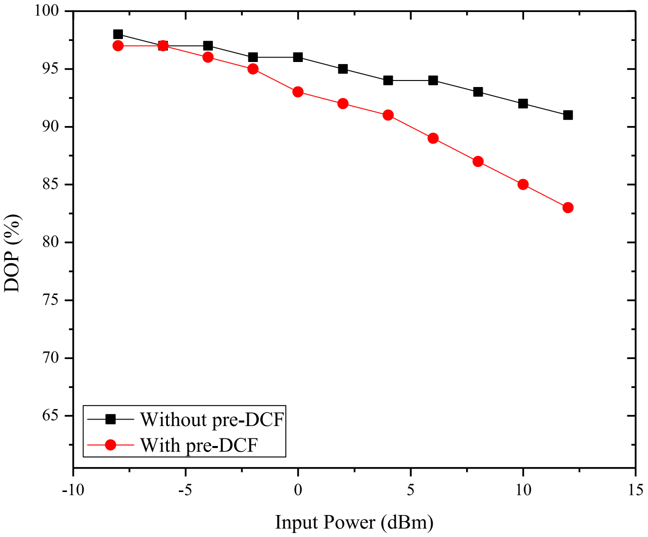


Fig. 8. XPolM induced depolarization of 120 Gbps polarization and subcarrier multiplexed signal with and without pre-DCF at 193.1 THz wavelength signal.

4. Conclusion

In this paper, nonlinear polarization effect imposed by 120 Gbps polarization and subcarrier multiplexed unicast and 40 Gbps DPSK multicast signal on performance of hybrid WDM/OTDM multicast overlay system has been analyzed by using pre-DCF in multicast enable and disable mode. We have investigated that XPolM effect induced nonlinear cross polarization scattering which degrade the Q-factor performance of hybrid WDM/OTDM system for dispersion management considered. The use of pre-DCF suppress the nonlinear polarization effect induced by fiber birefringence and improve the system performance but at higher power level (>5 dBm) degree of polarization (DOP) of orthogonally modulated signal linearly decreases. Higher power become the main constrain for data dependent SOP signals. At lower power level (<5 dBm), nonlinear polarization scattering imposed by orthogonally modulated signal can greatly suppress in the dispersion managed system.

Acknowledgment

S. Singh would like to thank the authorities of Sant Longowal Institute of Engineering and Technology, Longowal, India for providing fellowship (SRF) and research facilities.

References

[1] S. Singh, S. Singh, R. Kaur, and R. S. Kaler, “Performance investigation of optical multicast overlay system using orthogonal modulation format,” *Opt. Commun.*, vol. 338, pp. 58–63, 2015.
[2] Y. Zhang, N. Deng, C. K. Chan, and L. K. Chen, “A multicast WDM-PON architecture using DPSK/NRZ orthogonal modulation,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 17, pp. 1479–1481, Sep. 2008.
[3] S. Singh and S. Singh, “Investigation on four wave mixing effect in various optical fibers for different spectral efficient orthogonal modulation formats,” *Opt. Laser Technol.*, vol. 76, pp. 64–68, Jan. 2016.
[4] Y. Shao *et al.*, “Novel optical orthogonally modulation schemes for superimposing DPSK signal on dark RZ signal,” *Opt. Commun.*, vol. 281, no. 4, pp. 3658–3667, 2008.
[5] Y. Shao and N. Chi, “High spectral-efficiency 100 Gb/s transmission using DRZ, DQPSK and PolSK three dimension orthogonal modulation,” *Opt. Commun.*, vol. 285, no. 6, pp. 1049–1052, 2012.
[6] J. Yu *et al.*, “400 GB/s (4 × 100 Gb/S) Orthogonal PDM-RZ-QPSK DWDM signal transmission over 1040 km SMF-28,” *Opt. Exp.*, vol. 17, no. 20, pp. 17928–17933, 2009.
[7] S. Singh and S. Singh, “Performance analysis of hybrid WDM-OTDM optical multicast overlay system employing 120 Gbps polarization and subcarrier multiplexed unicast signal with 40 Gbps multicast signal,” *Opt. Commun.*, vol. 385, pp. 36–42, 2016.

[8] C. Xie, "Inter-channel nonlinearities in coherent polarization-division-multiplexed quadrature-phase-shift-keying systems," *IEEE Photon. Technol. Lett.*, vol. 21, no. 5, pp. 274–276, Mar. 2009.
[9] C. Xie, "WDM coherent PDM-QPSK systems with and without inline optical dispersion compensation," *Opt. Exp.*, vol. 17, no. 6, pp. 4815–4823, 2009.
[10] J. Lee, K. Park, C. Kim, and Y. Chung, "Effects of nonlinear crosstalk in optical PMD compensation," *IEEE Photon. Technol. Lett.*, vol. 14, no. 8, pp. 1082–1084, Aug. 2002.
[11] C. Xie, L. Möller, D. C. Kilper, and L. F. Mollenauer, "Impact of cross phase modulation induced polarization scattering on optical PMD compensation in WDM systems," *Opt. Lett.*, vol. 28, pp. 2303–2305, 2003.
[12] G. Charlet, J. Renaudier, O. Bertran Pardo, P. Tran, H. Mardoyan, and S. Bigo, "Performance comparison of singly-polarized and polarization- multiplexed at 10 Gbaud under nonlinear impairments," presented at the *Optical Fiber Commun. Conf./Nat. Fiber Opt. Eng. Conf.*, San Diego, CA, USA, 2008, Paper OThU8.
[13] H. Sunnerud, M. Karlsson, C. Xie, and P. Anderkson, "Polarization- mode dispersion in high-speed fiber-optic transmission systems," *J. Lightw. Technol.*, vol. 20, no. 12, pp. 2204–2219, Dec. 2002.
[14] D. G. Casillas and S. Stepanov, "Polarization insensitive homodyne detection of optical phase modulation by two-wave mixing in saturable Er-doped fiber," *Opt. Commun.*, vol. 283, pp. 1134–1137, 2010.
[15] S. Zhang, Y. Liu, Y. Liu, and H. J. S. Dorren, "All-optical sampling exploiting nonlinear polarization rotation in a single semiconductor optical amplifier," *Opt. Commun.*, vol. 285, pp. 1001–1004, 2012.
[16] X.-P. Xie, J.-G. Zhang, W. Zhao, and Y. Wen, "Analysis of polarization dependence for OTDM demultiplexers based on four-wavelength mixing in semiconductor optical amplifier," *Opt. Commun.*, vol. 281, pp. 958–964, 2008.
[17] M. Samiul Habib, R. Ahmad, M. Selim Habib, and S. M. A. Razzak, "Maintaining single polarization and dispersion compensation with modified rectangular microstructure optical fiber," *Optik*, vol. 125, pp. 4030–4034, 2014.
[18] H. Zhou, J. He, Z. Cao, and L. Chen, "All-optical wavelength conversion scheme to reduce the crosstalk among the two multiplexed channels for polarization multiplexing system," *Opt. Fiber Technol.*, vol. 19, pp. 549–555, 2013.
[19] M. Lin, Y. Zhang, J. Zhang, X. Yuan, M. Zhang, and Y. Huang, "Mitigation of nonlinear effects in 112-Gb/s transmission at 50-GHz channel spacing with multi-rate neighbors," in *Proc. Int. Conf. SPIE-OSA-IEEE Asia Commun. Photon.*, 2011, vol. 8309, pp. 83092V-1–83092V-6.
[20] C. Bock and J. Prat, "WDM/TDM PON experiments using the AWG free spectral range periodically to transmit unicast and multicast data," *Opt. Exp.*, vol. 13, no. 8, pp. 2887–2891, 2005.
[21] X. Liu *et al.*, "Experimental demonstration of joint SPM compension in 44 Gb/s PDM-OFDM transmission with 16 QAM subcarrier modulations," in *Proc. 25th Eur. Conf. Opt. Commun.*, 2009, Paper 2.3.4.
[22] Q. J. Chang *et al.*, "Simultaneously transmission of point to point data and selective delivery of video services in a WDM-PON using ASK/SCM modulation format," in *Proc. Int. Conf. Opt. Fiber Commun./Nat. Fiber Opt. Eng.*, 2008, Paper OWH2.
[23] Y.-H. Wen and K.-M. Feng, "A simple NRZ-OOK to PDM RZ-QPSK optical modulation format conversion by bidirectional XPM," *IEEE Photon. Technol. Lett.*, vol. 27, no. 9, pp. 935–938, May 2015.
[24] M. Winter, D. Setti, and K. Petermann, "Cross-polarization modulation in polarization-division multiplex transmission," *IEEE Photon. Technol. Lett.*, vol. 22, no. 8, pp. 538–540, Apr. 2010.
[25] S. Wabnitz, "Cross-polarization modulation domain wall solitons for WDM signals in birefringent optical fibers," *IEEE Photon. Technol. Lett.*, vol. 21, no. 13, pp. 875–877, Jul. 2009.
[26] F. Yaman and G. Li, "Nonlinear impairment compensation for polarization-division multiplexed WDM transmission using digital backward propagation," *IEEE Photon. J.*, vol. 2, no. 5, pp. 816–831, Oct. 2010.
[27] G. P. Agrawal, *Nonlinear Fiber Optics*, 4th ed. San Diego, CA, USA: Academic, 2007.
[28] G. P. Agrawal, *Fiber–Optic Communication System*, 3rd ed. Singapore: Wiley, 2002.
[29] L. Yin, J. Zhang, P. M. Fauchet, and G. P. Agrawal, "Optical switching using nonlinear polarization rotation inside silicon waveguides," *Opt. Lett.*, vol. 34, no. 4, pp. 476–478, Feb. 2009.
[30] Q. Lin, O. J. Painter, and G. P. Agrawal, "Nonlinear optical phenomena in silicon waveguides: Modeling and applications," *Opt. Exp.*, vol. 15, no. 25, pp. 16604–16644, 2007.
[31] C. Xie, "Impact of nonlinear and polarization effects in coherent systems," *Opt. Exp.*, vol. 19, no. 26, pp. B915–B930, Dec. 2011.
[32] C. Xie, "Nonlinear polarization effects and its mitigation in polarization division multiplexed coherent transmission system," *Chin. Opt. Lett.*, vol. 8, no. 9, pp. 844–851, 2010.
[33] R. Killey, H. Thiele, V. Mikhailov, and P. Bayvel, "Reduction of intra-channel nonlinear distortion in 40 Gb/s-based WDM transmission over standard fiber," *IEEE Photon. Technol. Lett.*, vol. 12, no. 12, pp. 1624–1626, Dec. 2000.