Front. Optoelectron. 2013, 6(3): 312–317
DOI 10.1007/s12200-013-0332-z

RESEARCH ARTICLE

Impact of polarization mode dispersion and nonlinearities on 2-channel DWDM chaotic communication systems

Bushra NAWAZ, Rameez ASIF (✉)

Telecommunication Engineering Department, University of Engineering & Technology, Taxila 47050, Pakistan

Abstract This paper has designed 2-channel dense wavelength division multiplexing (DWDM) chaotic system at the frequencies of 193.1 and 193.2 THz, respectively. The optical chaotic signals were produced by using the semiconductor laser that is numerically modeled by employing laser rate equations. These two channels were multiplexed and then propagated through single mode optical fiber (SMF) of 80 km length with dispersion compensating fiber of 16 km length. Erbium doped fiber amplifier (EDFA) was used to compensate the power losses in the SMF. In this paper, we investigated the effects of polarization mode dispersion (PMD) and nonlinearities especially stimulated Raman scattering (SRS) on 2 channel DWDM chaotic communication system by varying the length of the SMF and value of differential group delay (DGD).

Keywords chaos, chaotic signal, chaotic synchronization, dense wavelength division multiplexing (DWDM) chaotic communication, polarization mode dispersion (PMD), stimulated Raman scattering (SRS)

1 Introduction

In the early 1990s, the discovery of possibility of chaotic synchronization by Pecora and Carroll triggered the idea to use chaotic synchronization to provide security in digital and optical communication [1]. Chaos is a complex irregular and un-predictable behavior shown by a simple deterministic system. There are many software algorithms, which provide security using different software encryption techniques. These algorithms provide security to some extent but not enough. A parameter known as key is used to secure the transmission system. The algorithm is more complex and secured if the length of the key is longer. If some hacker tries to hack the system, he can persuade transmitter and receiver to use his own key, which makes transmission of information completely transparent to him. Chaotic communication is a simple and alternative solution. In this type of communication system, chaotic carrier is modulated with the message signal and transmitted along the fiber and at receiver end this chaotic carrier is again produced by performing synchronization to subtract the message plus chaotic signal to obtain the original message signal [2]. The practical demonstration of chaos for secure communication in metropolitan area network of Athens, Greece has marked the start of commercialization of chaos based secure optical networks [3]. Dense wavelength division multiplexing (DWDM) chaos is the promising technique for future providing security and bandwidth [4–6]. DWDM technology gives us maximum utilization of available bandwidth in optical fiber [7]. The available bandwidth can be used optimally by decreasing the channel spacing and increasing data rate per channel. Polarization mode dispersion (PMD) and nonlinearities are the major limiting factors in long distance communication [8–10]. Stimulated Raman scattering (SRS) and four wave mixing (FWM) are two main causes of crosstalk in the DWDM system because of narrow channel spacing, whereas the FWM is not apparent at two channels DWDM system. PMD and nonlinearities combined effects cannot be ignored at long distances, at higher bit rate and in the systems where narrow channel spacing is used. It also increases the parameter mismatch between the transmitted and received chaotic signal. Previous studies on the analysis of nonlinear effects have been reported on the phase-encoded transmission that includes the study on different post-processing techniques [11,12], pulse shapes [13] and encoding techniques [14]. However, these studies are limited to evaluate the impact of deterministic impairments, hence neglecting the effect of PMD. In this paper, we have evaluated the combine effect of PMD and nonlinear effect on the on 2-channel DWDM chaotic communication system.

Received April 18, 2013; accepted May 14, 2013

E-mail: rameez.asif@uettaxila.edu.pk

2 Simulation model

Chaotic signal is generated using semiconductor laser, which is governed by the following laser rate equations. Dynamical behavior of semiconductor laser can be described effectively by laser rate equations. The modulation dynamics of the laser are modeled by coupled rate equations, which describe the relationship between the carrier density $N(t)$, photon density $S(t)$, and optical phase $\varphi(t)$ [15].

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t}=\frac{I(t)}{q(V)}-g_0\Big(N(t)-N_{\mathrm{t}}\Big)\frac{1}{1+\varepsilon S(t)}S(t), \tag{1}$$

$$\frac{\mathrm{d}S(t)}{\mathrm{d}t}=\varGamma g_0(N(t)-N_{\mathrm{t}})\frac{1}{1+\varepsilon S(t)}S(t)-\frac{S(t)}{\tau_{\mathrm{p}}}$$
$$=\varGamma\beta N(t)/\tau_{\mathrm{p}}, \tag{2}$$

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t}=\frac{1}{2}\alpha\left[\varGamma g_0\Big(N(t)-N_{\mathrm{t}}\Big)-\frac{2}{\tau_{\mathrm{p}}}\right], \tag{3}$$

$$g_0=v_{\mathrm{g}}a_0, \tag{4}$$

$$I_{\mathrm{t}}=I_{\mathrm{DC}}+I_{\mathrm{IN}}I_{\mathrm{PK}}, \tag{5}$$

where, g_0 is the gain slope constant. I_{t} is the internal signal current, I_{IN} is the input current, I_{DC} is the parameter bias current (I_{DC} = 33 mA) and I_{PK} is the parameter modulation current (I_{PK} = 10 mA). Table 1 gives the values of the semiconductor laser that is essential to produce the chaos waveform.

Figure 1 is the block diagram of the proposed model. We have used frequencies at 193.1 and 193.2 THz with a channel spacing of 0.1 THz, which is recommended by ITU for standard DWDM system while the bit rate is 5 Gbit/s. These two signals are multiplexed using 2×1 multiplexer with 100 GHz bandwidth and 0 dB insertion losses. Afterwards the multiplexed signal is amplified using gain control Erbium doped fiber amplifier (EDFA), and then this amplified signal is propagated through the optical fiber. The length of single mode optical fiber is 80 km with dispersion of 16 ps/nm-km and attenuation of 0.2 dB/km. Dispersion is compensated using dispersion compensation fiber (DCF). DCF length is 16 km with –83.75 ps/nm-km to counter balance the dispersion of single mode optical fiber.

Table 1 Values of parameters of semiconductor laser

symbol	parameter	value
a_0	active layer coefficient	1.5e–9
v_{g}	group velocity	8.5e9 cm/s
ε	gain compression factor	1e – 17 cm^3
N_{t}	carrier density transparency	1e18 cm^{-3}
β	fraction of spontaneous emission coupled into the lasing mode	8e–7
$\varGamma$	mode confinement factor	0.4
V	active layer volume	1.5e–10 cm^3
τ_{p}	photon life time	3e–12 s
τ_{N}	electron life time	1e–9 s
A	line width enhancement factor	5

The chaotic signal produced from our numerical model is plotted as a function of the signal output power and time. Figure 2(a) is the transmitted chaotic signal and Fig. 2(b) is the received chaotic signal in the absence of polarization mode dispersion and nonlinearities effects. An ideal fiber has perfect core and symmetry so two modes of light which are perpendicular to each traveling in the ideal optical fiber will not suffer PMD effects. But in real fiber, the core is not perfect so these two perpendicular modes will not travel with the same speed resulting in spreading of the pulses. Differential group delay is directly proportional to the square root of distance.

$$\Delta\tau=D_{\mathrm{PMD}}\mathrm{sqrt}(L), \tag{6}$$

where D_{PMD} is the PMD parameter of the fiber, typically measured in ps/sqrt(km), a measure of the strength and frequency of the imperfection of the real fibers (sqrt stands for square root of the variable). PMD is a stochastic

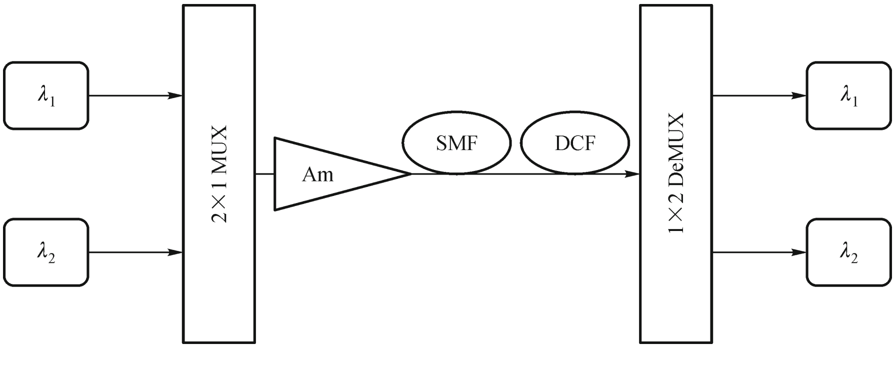


Fig. 1 Block diagram of chaotic DWDM system

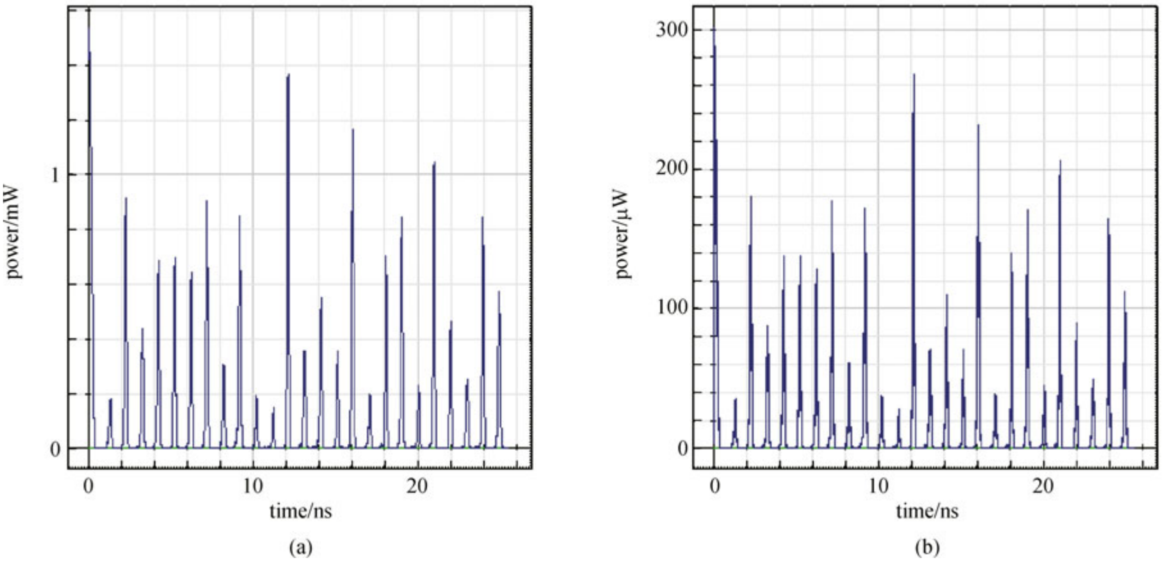


Fig. 2 Chaotic signal at transmitter (a) and receiver (b)

process with a random differential group delay (DGD) value. In this work, we vary the values of DGD to examine the effects of polarization mode dispersion. The combined effects of PMD and nonlinearities are also numerically investigated. SRS causes the power leakage from the shorter wavelength to the higher wavelength due to Raman scattering in the optical fiber. The power fractions leaked from the higher frequencies components to the lower frequency components [16] are given in Eq. (7).

$$D=\sum_{n=1}^{N-1}\left(\frac{f_0 p_n g_n L_{\mathrm{ef}}}{f_n A_{\mathrm{ef}}}\right), \tag{7}$$

where, p_n is the original power of the lowest frequency component, f_0 is channel with lowest frequency, i.e., 1551.72 nm, f_n is the highest frequency channel, i.e., 1552.52 nm, N is the total number of channels, i.e., 2, L_{ef} is the effective length of fiber, i.e., 20 km A_{ef} is the effective area of fiber, i.e., 80 μm^2 and g_n is the Raman gain coefficient relating the high frequency component to the lowest frequency component, i.e., 3.15 dB/(km·W). The remaining power at the lowest frequency channel is given by Eq. (8).

$$P_{\mathrm{rem}}=-10\log(1-D). \tag{8}$$

3 Results and discussion

3.1 Synchronization graphs

In this paper, system performance is analyzed by evaluating the synchronization graphs. The synchronization graphs were plotted between the power of the transmitted chaotic signal and power of the received chaotic signal. If there is straight line, it shows that system is synchronized; but if deviates from the straight line, then the signal is effected by nonlinear effects and PMD.

Figure 3 is the synchronization graph of channel 1 plotted between the received and transmitted power of chaotic signal, which is propagated at a distance of 80 km and at a bit rate of 5 Gbit/s. In these synchronization graphs, we neglect the nonlinear effects to only observe the PMD effects. In Fig. 3(a), the value of DGD is 0 ps/km and we can see that synchronization is better, and it is only affected by the high value of attenuation in DCF. In Figs. 3(b) and 3(c), the value of DGD is 0.5 and 1.0 ps/km respectively from the given figures. It is clear that with the increase in the value of DGD, the parameter mismatch increases and greatly affecting the chaotic synchronization.

Figure 4 is the synchronization graph plotted in the presence of PMD and nonlinear effects simultaneously, while the values of DGD are 0, 0.5 and 1.0 ps/km are kept in Figs. 4(a), 4(b) and 4(c) respectively. By analyzing these graphs, we can say that polarization mode dispersion and nonlinear effects are major degrading sources and severely affect the chaotic signal during transmission through the optical fiber.

Crosstalk in the DWDM is important degrading factor, and it is induced by the presence of FWM mixing and SRS. In 2-channel DWDM systems, FWM is not apparent because for FWM at least 3 signals should be presented, so the crosstalk in this system is presented mainly due to SRS [16]. Figure 5 is the frequency spectrum of our system that

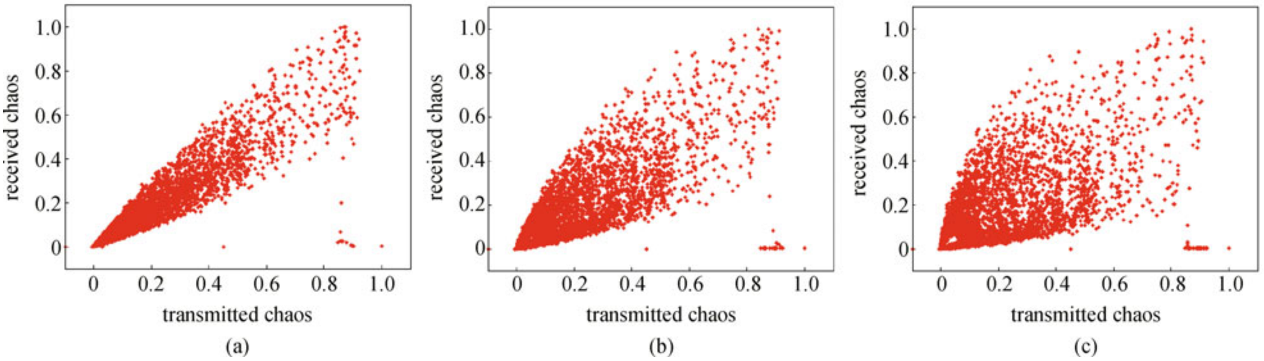


Fig. 3 Synchronization graphs with parameter of PMD at (a) 0; (b) 0.5 and (c) 1.0 ps/km

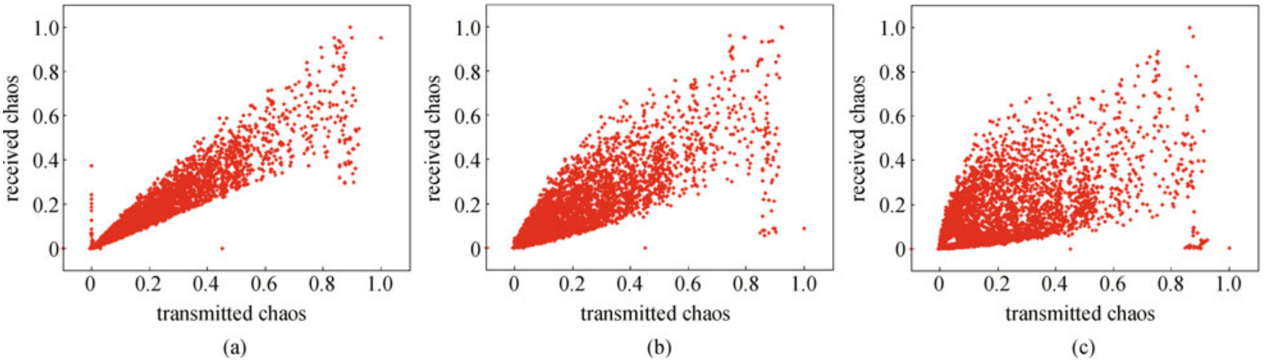


Fig. 4 Synchronization graphs with parameter of PMD at (a) 0, (b) 0.5 and (c) 1.0 ps/km including nonlinear effects

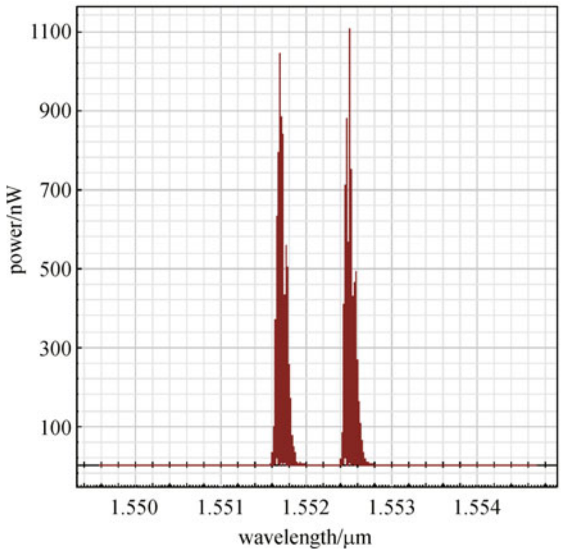


Fig. 5 Frequency spectrum showing SRS

shows the power leakage from channel 2 to channel 1, while channels 1 and 2 are at frequency of 193.1 and 193.2 THz respectively.

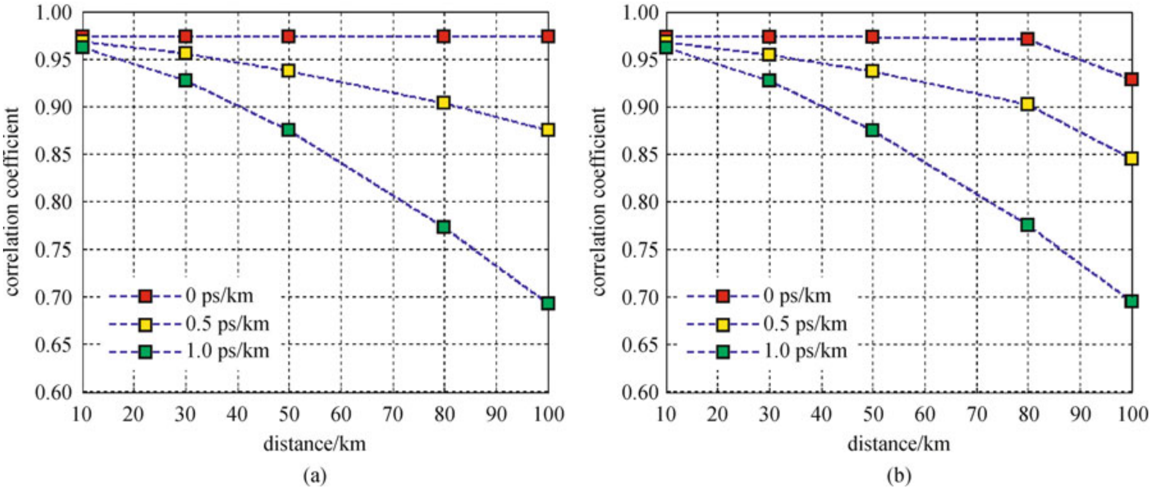
3.2 Correlation coefficient

To determine the chaotic synchronization, correlation coefficient (*CC*) [15] can be defined in Eq. (9).

$$CC = \frac{\langle [P_{\mathrm{T}}(t) - P_{\mathrm{T}}(t)][P_{\mathrm{R}}(t) - P_{\mathrm{R}}(t)] \rangle}{\sqrt{\langle [P_{\mathrm{T}}(t) - P_{\mathrm{T}}(t)]^2 \rangle \langle [P_{\mathrm{R}}(t) - P_{\mathrm{R}}(t)]^2 \rangle}}, \qquad (9)$$

where, $P_{\mathrm{T}}(t)$ and $P_{\mathrm{R}}(t)$ are the transmitted and received powers of the chaotic signal. The value of *CC* varies from -1 to 1. The more the value approaches to 1, the better the synchronization. *CC* graphs are plotted against various length of the optical fiber at different value of PMD. We have plotted the values *CC*s factor versus distance at different values of DGD with a bit rate of 5 Gbit/s. The main reason of adopting this performance comparison methodology is that due to the statistical properties of the optical chaos (that are usually not Gaussian) and hidden nature of a digital message in secure transmission schemes, therefore it is not advisable to directly calculate BER of the chaotic transmission.

In Fig. 6(a), we have only considered the PMD effects and neglected the nonlinear effects, while in Fig. 6(b) the nonlinear effects are also included. DGD of 0, 0.5 and



(a) (b)

Fig. 6 Correlation coefficient versus distance. (a) Only PMD effects; (b) both PMD and nonlinear effects

1.0 ps/km are shown here with marker color of red, yellow and green respectively. It can be observed from Fig. 6 that at the smaller distances, e.g., at 10 km, the higher values of DGD is effecting the chaotic synchronization in small extent but with the increase in distance correlation coefficient values decreases results in more degradation in system performances. The combined effects of PMD and nonlinearities are making chaotic synchronization worse than the alone effects of PMD on chaotic synchronization. In both the cases of DGD 0 and 0.5 ps/km at 100 km transmission distance, we have observed a clear degradation in *CC* values. However, for the higher values of DGD such as 1 ps/km, the transmission performance is highly degraded and it is hard to differentiate and estimate the signal quality at this point for both the cases.

4 Conclusions

In this paper, we numerically investigated the effects of PMD and nonlinearities on the DWDM chaotic system. A 2-channel DWDM system was designed, in which channels are transmitting at channel spacing set by international standards. We analyzed the effects of PMD and nonlinearities at various distance and DGD. It is observed that with the increase in DGD and distance of the installed fiber, these effects will highly degraded the signal quality, which result in the increase of parameter mismatch between the transmitter and receiver. Chaos based encryption is a promising technology, although it is still under experimental setup. PMD is a stochastic process and it can be compensated using polarization-tracking devices, but these techniques are not highly recommendable. Nonlinearities can be mitigated by increasing channel spacing, decreasing power and using different signal processing methods to avert the effects of self phase modulation, cross phase modulation and SRS.

Acknowledgements The author would like to thank Prof. Dr. Bernhard Schmauss for his ever-lasting support during the research stay at University of Erlangen-Nuremberg, Germany. We will also thank Mr. Fazal Abbas, Department of Physics, IIU Islamabad, Pakistan for the value discussion and his guidance.

References

1. Pecora L M, Carroll T L. Synchronization in chaotic systems. Physical Review Letters, 1990, 64(8): 821–824
2. Donati S, Mirasso C R. Introduction to the feature section on optical chaos and applications to cryptography. IEEE Journal of Quantum Electronics, 2002, 38(9): 1138–1140
3. Argyris A, Syvridis D, Larger L, Annovazzi-Lodi V, Colet P, Fischer I, Garcı´a-Ojalvo J, Mirasso C R, Pesquera L, Shore K A. Chaos-based communications at high bit rates using commercial fibre-optic links. Nature, 2005, 438(7066): 343–346
4. Ali S Z, Islam M K, Zafrullah M. Effect of parametric variation on generation and enhancement of chaos in erbium-doped fiber-ring lasers. Optical Engineering, 2010, 49(10): 105002-1–105002-12
5. Zhang F, Chu P L, Lai R, Chen G R. Dual-wavelength chaos generation and synchronisation in erbium-doped fiber lasers. IEEE Photonics Technology Letters, 2005, 17(3): 549–551
6. Zhang J Z, Wang A B, Wang J F, Wang Y C. Wavelength division multiplexing of chaotic secure and fiber-optic communications. Optics Express, 2009, 17(8): 6357–6367
7. Luo L G, Chu P L. Optical secure communications with chaotic erbium-doped fiber lasers. Journal of the Optical Society of America B, Optical Physics, 1998, 15(10): 2524–2530
8. Menyuk C R, Marks B S. Interaction of polarization mode dispersion and nonlinearity in optical fiber transmission systems. Journal of Lightwave Technology, 2006, 24(7): 2806–2826
9. Zhang F, Chu P L. Effect of transmission fiber on chaos

communication system based on erbium-doped fiber ring laser. Journal of Lightwave Technology, 2003, 21(12): 3334–3343

10. Argyris A, Grivas E, Bogris A, Syvridis D. Transmission effects in wavelength division multiplexed chaotic optical communication systems. Journal of Lightwave Technology, 2010, 28(21): 3107–3114
11. Asif R, Lin C Y, Holtmannspoetter M, Schmauss B. Multi-span digital non-linear compensation for dual-polarization quadrature phase shift keying long-haul communication systems. Optics Communications, 2012, 285(7): 1814–1818
12. Asif R, Lin C Y, Schmauss B. Impact of channel baudrate on logarithmic digital backward propagation in DP-QPSK system with uncompensated transmission links. Optics Communications, 2011, 284(24): 5673–5677
13. Asif R, Usman M, Lin C Y, Schmauss B. Application of a digital non-linear compensation algorithm for evaluating the performance of root-raised-cosine pulses in 112 Gbit/s DP-QPSK transmission. Journal of Optics, 2012, 14(9): 095402
14. Asif R, Lin C Y, Holtmannspoetter M, Schmauss B. Evaluation of correlative coding and DP-16QAM *n*-channel 112 Gbit/s coherent transmission: digital non-linear compensation perspective. Optics Express, 2013, 21(1): 781–788
15. Agrawal G P. Nonlinear Fiber Optics. 3rd ed. San Diego: Academic Press, 2001
16. Pietrzyk S, Szczesny W, Marciniak M. Power penalty caused by stimulated Raman scattering in WDM systems. Journal of Telecommunications And Information Technology, 2000, 1(2): 52–58