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Theoretical Study on Hybrid Amplification of 32-Channels DWDM in Optical Parametric Amplifiers

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Wan Maisarah Mukhtar[1,2,*], Alia Athira Tarmuji[1], Noor Syuhaida Mohamed[1], Muhammad Syahir Jafree[1]

[1] Applied Physics Programme, Faculty of Science and Technology, Universiti Sains Islam Malaysia (USIM), Bandar Baru Nilai, Negeri Sembilan, Malaysia
[2] Frontier Materials Research Group (FMRG), Faculty of Science and Technology, Universiti Sains Islam Malaysia (USIM), Bandar Baru Nilai, Negeri Sembilan, Malaysia

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ABSTRACT

With the increasing demand for greater quality of transferred data, the optical cable lines are reaching their limits of transfer capacities. The alternative for more effective usage is by introducing the Dense Wavelength Division Multiplexing (DWDM) integrated with optical amplifier to optimize the output signal. This study was performed theoretically with an assistance of OptiSystem 9.0 simulation software to develop higher transfer speed of 32 channels DWDM network system by employing hybrid optical amplifiers. Three types of optical amplifiers had been introduced such as Erbium Doped Fiber Amplifier (EDFA), Semiconductor Optical Amplifier (SOA) and Dynamic RAMAN amplifier. The optimum performance of DWDM system was obtained by employed hybrid EDFA-Raman amplifier which resulted the best transmission signal received with maximum Qfactor=43.0579 a.u. The hybrid EDFA-Raman produced better stability than EDFA-SOA where the received signals were only fluctuated within ±3.73 a.u. In comparison with other types of configuration, namely EDFA-SOA and RAMAN-SOA; the value of maximum Q-factor experienced about 50% of increment. In conclusion, the development of high performance and excellent stability of 32-channels DWDM optical network system can be achieved by introduced hybrid amplifier of EDFA-RAMAN.

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1. Introduction

Dense wavelength division multiplexed (DWDM) systems have become the typical technology in high capacity optical telecommunication networks ranging in distance from a few kilometers to thousands of kilometers [1-3]. Implementing DWDM system involves maximizing the rate of transmitter information while minimizing the limitation of the existing physical network. In a long-distance networks, the signal traveling inside the fiber usually suffers several losses such as fiber

* *Corresponding author.*
E-mail address: Wan Maisarah Mukhtar (sapuan@upm.edu.my)

attenuation losses, fiber tap losses and fiber splice losses [4]. High losses issue will cause to the degradation of signal quality at receiver part. To overcome this problem, researchers and engineers have conducted few significant works to increase the transmission limits and to enhance the quality of received signals by introducing the concept of space-division multiplexing (SDM) [5-8] and adding active components such as repeaters and optical amplifiers to boost the received signals [9-11] in the DWDM optical networks.

The conventional optical amplifiers such as Erbium Doped Fiber Amplifier (EDFA) and Raman amplifier are the vital components for DWDM systems which have been introduced in optical networks system around 1980s. EDFA is highly transparent to signal format and bit rate and highly immune to interference effects between different channels so only EDFA has been chosen for long distance transmission [12-13]. Nonetheless, the EDFA only able to amplify the optical signal separately for each band. Distributed Raman amplification (DRA) provides impressive features by offering much lower effective noise figure than EDFA gain [14-15]. The main drawback of DRA is the occurrence of Rayleigh scattering which reduce its performance quality. The weakness of Raman amplification is also due to its spectrum which is not the inherently. Another type of common amplifier which is usually deployed in optical network system is semiconductor amplifier (SOA). The development of semiconductor optical amplifier offered significant reductions in size and power consumption compared with the EDFA, yet suffers higher noise figures and data-patterning crosstalk in WDM applications. The most common techniques in analyzing the quality of received signal is by performing an eye diagram test [16]. Signal-distorting effects will cause the eye opening to get smaller and vice-versa. Few significant characterizations such as BER contour, maximum Q-factor, optical signal-to-noise ratio (OSNR) and minimum BER analyses also help to indicate the performance of receiver [17-19].

This work proposed the hybridization of various types of optical amplifiers such as EDFA-SOA, EDFA-Raman and Raman-SOA to increase the quality of received signals by studying the important optical parameter at the receiver part. By using simulation approach, we focused on the analysis of Q-factor, bit-error-rate (BER) and eye diagram pattern to investigate the quality of output signal. We managed to prove that the optimum signal quality able to be obtained by deployed hybrid EDFA-Raman amplifier in 32 channels DWDM optical system.

2. Methodology

2.1 Construction of 32-channels Dense Wavelength Division Multiplexing (DWDM) Network System

This work was conducted theoretically using OptiSystem 9.0 simulation software by OPTIWAVE System Inc. A 32 channels DWDM optical network with channel spacing of 100 GHz and return-to-zero (RZ) modulation format has been developed. Laser source of $\lambda = 1550nm$ was transmitted along a single mode fiber (SMF) for data transmission. The length of the SMF and dispersion compensation fiber (DCF) were fixed as 50 km and 10 km respectively. Due to fiber attenuation issue, the employment of optical amplifier was believed able to enhance the poor signal. In this study, three types of hybrid optical amplifier had been introduced such as hybrid Erbium Doped Fiber Amplifier (EDFA)-Semiconductor Optical Amplifier (SOA), hybrid EDFA-Raman and hybrid Raman-SOA with a gain of 10dB and noise figure of -6 dB. By referring on eye diagram pattern, the optimal length of EDFA and Raman were set as 5 m and 20 km respectively. Figure 1 displays the optical link design of various hybrid amplifiers namely EDFA-SOA (Fig. 1(a)), EDFA-Raman (Fig. 1(b)) and Raman-SOA (Fig. 1(c)). These optical amplifiers owned amazing features by considering their ability to pump the

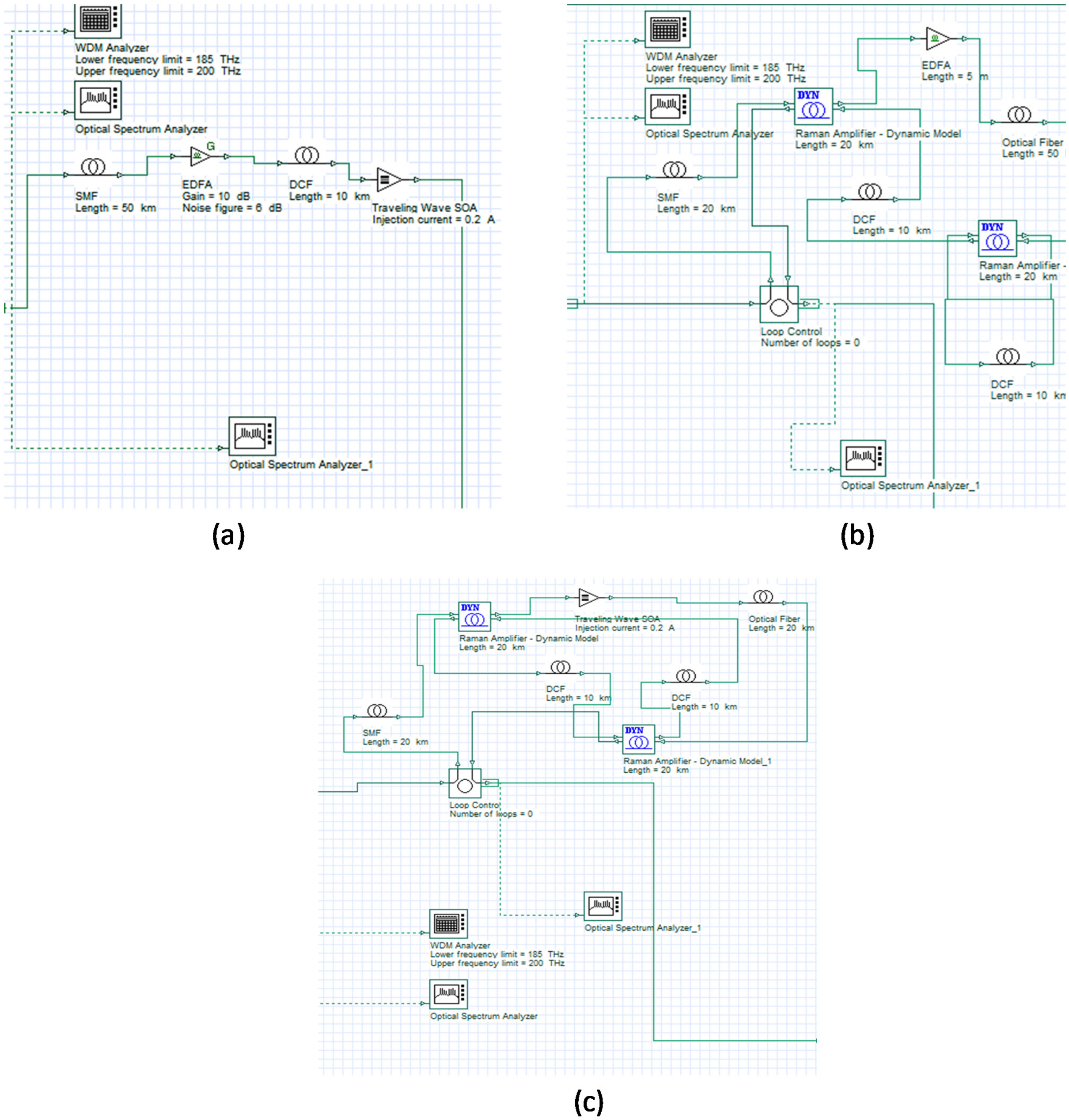


Fig. 1. Layout of fiber optical link of DWDM system for various hybrid configurations of optical amplifier (a) Hybrid EDFA-SOA (b) b) Hybrid EDFA-RAMAN (c) Hybrid RAMAN-SOA

devices at different wavelength which is suitable for DWDM, very low coupling losses to the compatible sized fiber transmission medium and minimum dependence of gain on light polarization. The performance of proposed hybrid amplifiers in optical link was investigated by studying few important parameters such as maximum Q-factor, minimum BER pattern, height of the eye, threshold and the pattern of the eye diagram. The signal transmission stability was scrutinized by examining the characteristics of these important parameters at channel 1, 8, 16, 24 and 32. Table 1 shows list of controlled parameters of the components for the development of DWDM 32-channels in optical parametric amplifier.

Table 1
Controlled parameters and their specification of 32-channels DWDM network design for hybrid optical amplifier of EDFA-SOA, EDFA-RAMAN and RAMAN-SOA

Parameters	Value	Unit
Transmitter Frequency	1555	Nm
Modulation Type	Return-to-Zero (RZ)	
Frequency Spacing	100	GHz
Amplifier Lenghth:		
EDFA	5	m
RAMAN	40	km
Length of optical fiber (SMF)	40 and 50	Km
Length of DCF	20	km
Total Distance covered by SMF and DCF	60	km
Number of loop control	0	
Injection current of SOA	0.2 - 0.6	A

3. Results

3.1 Effect of Injection Current on Signal Pumping

To achieve maximum amplification, the injection current for signal pumping using SOA were varied between 0.2 A and 0.6 A. Table 2 until 6 shows the obtained values of parameters such as high Q-factor, minimum BER, eye height and threshold for hybrid EDFA-SOA as pump current was modulated. Evidently, the amount of amplifier-produced signal distortions started to increase as the current values exceeded 0.2 A which indicated minimum current led to the optimization of system performance. Throughout this work, we set the value of pump current as I=0.2 A for any hybrid configuration which consist of SOA.

Table 2
Recorded data for the parameters of hybrid EDFA-SOA with current 0.2 A for pumping the SOA

Parameters	Number of channels				
	1	8	16	24	32
Maximum Q-factor (a.u)	2.12394	5.7136	6.45795	5.06531	6.53665
Minimum BER (a.u)	0.014942	4.89E-09	4.75E-11	2.02E-07	2.77E-11
Eye Height (a.u)	-0.001995	0.00195083	0.00248049	0.00188328	0.00228069
Threshold (a.u)	0.00849674	0.00268974	0.00307332	0.00364159	0.00247696

Table 3
Recorded data for the parameters of hybrid EDFA-SOA with current 0.3 A for pumping the SOA

Parameters	Number of channels				
	1	8	16	24	32
Maximum Q-factor (a.u)	2.20404	4.26183	0	5.44153	5.65724
Minimum BER (a.u)	0.0120071	9.94E-06	1	2.44E-08	6.70E-09
Eye Height (a.u)	-0.0027057	0.00207776	0	0.00316161	0.00281776
Threshold (a.u)	0.0121587	0.0055202	0	0.00449778	0.0034837

Table 4
Recorded data for the parameters of hybrid EDFA-SOA with current 0.4 A for pumping the SOA

Parameters	Number of channels				
	1	8	16	24	32
Maximum Q-factor (a.u)	2.21264	3.79058	4.65066	4.80612	4.96871
Minimum BER (a.u)	0.0113644	6.88E-05	1.48375e-6	7.09132e-7	2.94854e-7
Eye Height (a.u)	-0.0036646	0.00172944	0.00342856	0.00354226	0.00299566
Threshold (a.u)	0.0179736	0.00612064	0.00713054	0.00601223	0.00445258

Table 5
Recorded data for the parameters of hybrid EDFA-SOA with current 0.5 A for pumping the SOA

Parameters	Number of channels				
	1	8	16	24	32
Maximum Q-factor (a.u)	3.32259	3.22004	4.20846	4.26835	4.44486
Minimum BER (a.u)	0.0004395	0.000594	1.23002e-5	9.03777e-6	3.8747e-6
Eye Height (a.u)	0.00102911	0.00071511	0.00350439	0.00348029	0.00290882
Threshold (a.u)	0.00964661	0.00812877	0.00961628	0.00743208	0.00535794

Table 6
Recorded data for the parameters of hybrid EDFA-SOA with current 0.6 A for pumping the SOA

Parameters	Number of channels				
	1	8	16	24	32
Maximum Q-factor (a.u)	0	0	2.98081	3.28748	4.03247
Minimum BER (a.u)	1	1	0.00143496	0.00044293	2.45E-05
Eye Height (a.u)	0	0	-9.63E-05	0.00120323	0.0026090
Threshold (a.u)	0	0	0.0148846	0.00807621	0.0062147

3.2 Performance Analysis on Hybrid EDFA-SOA

Figure 2 illustrates the maximum Q-factor of hybrid EDFA-SOA with injection current of 0.2 A at numerous selected channels namely channel 1, 8, 16, 24 and 32. In general, we found that the values of Q-factor for all channels were small which was within 2.12 a.u and 6.54 a.u. The smallest Q-factor was obtained at channel 1, meanwhile the maximum value was resulted at channel 32. Different values of Q-factor at channel 1, 8, 16, 24 and 32 indicated the instability of this optical link with small deviation of ±4.42 a.u. Figure 3 depicts the BER pattern for hybrid EDFA-SOA with pump current at 0.2 A. The BER patterns were not observed at channel 1, 8 and 24 due to low signal transmission (Fig. 2(a), (b) and (d)). A large contour pattern at channel 16 and 32 indicated strong signal distortion as illustrated in Fig. 2(c) and Fig. 2(e).

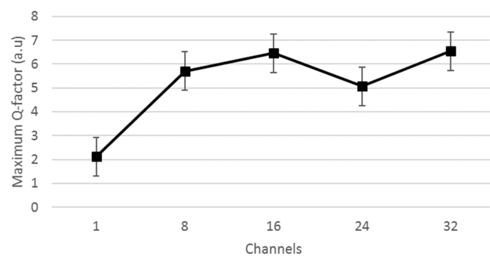


Fig. 2. Maximum Q-factor values of DWDM using hybrid EDFA-SOA with injection current 0.2 A

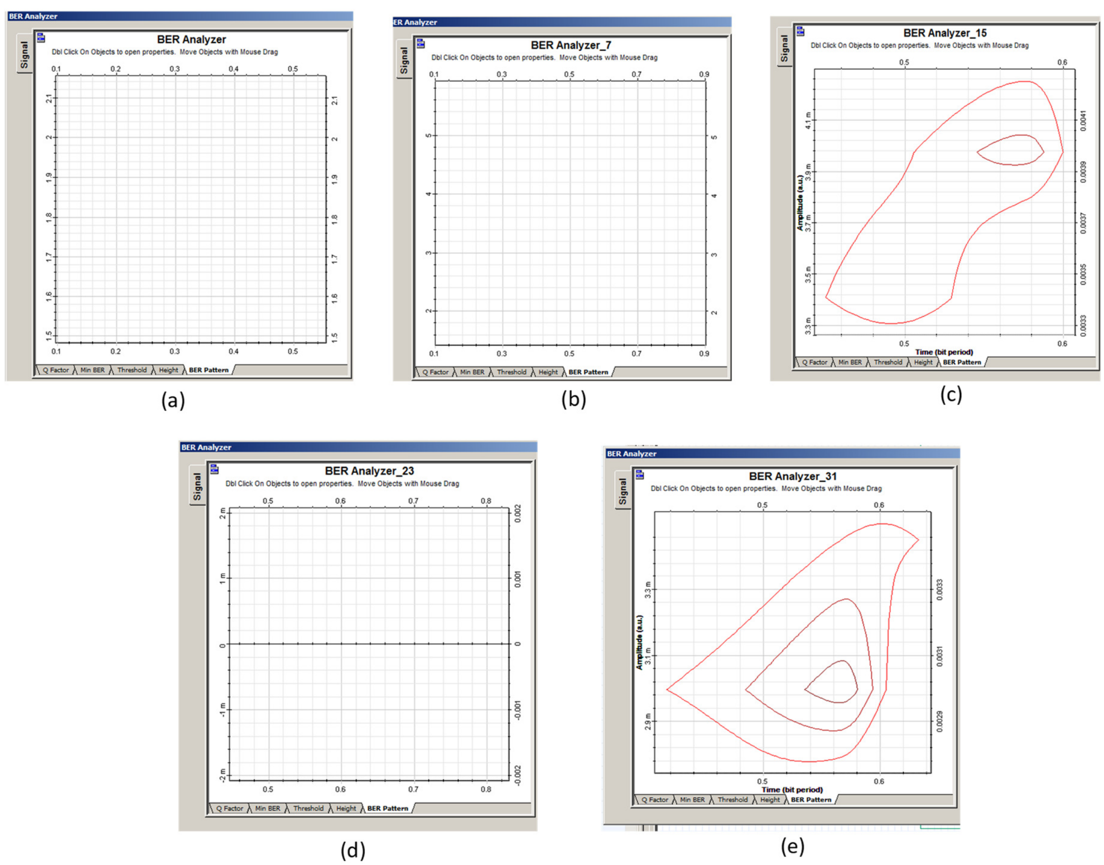


Fig. 3. BER pattern various number of channels of DWDM using hybrid EDFA-SOA (a) 1 (b) 8 (c) 16 (d) 24 (e) 32

The important of eye diagrams is to access the quality of a received signal. Figure 4 (a), (b), (c), (d) and (e) illustrate the eye diagram of hybrid EDFA-SOA for channel 1, 8, 16, 24 and 32 respectively. Channel 32 experienced the widest opening eye diagram as it owned the highest value of Q-factor in comparison with other channels which represented the minimum signal loss during signal transmission. The received pattern became wider on the sides and on top and bottom with the increment of channel numbers.

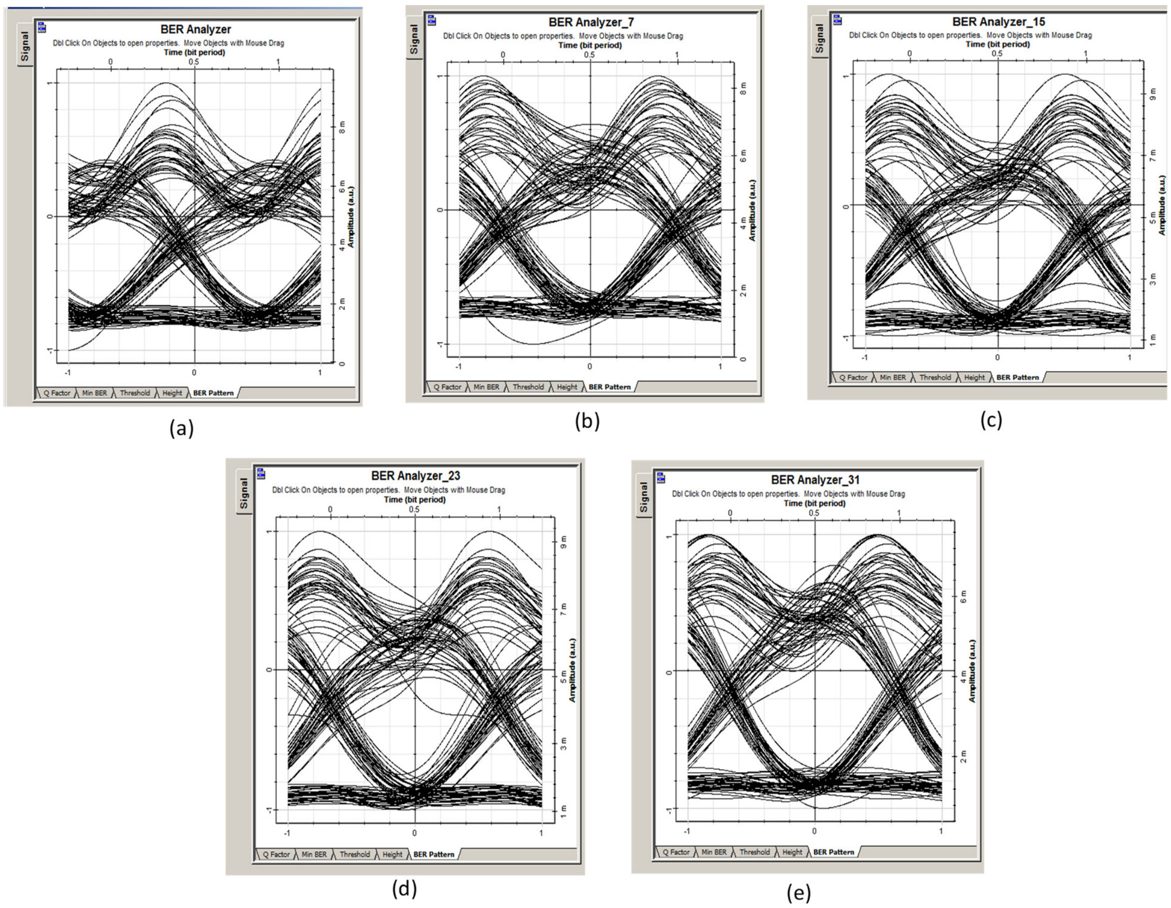


Fig. 4. Eye diagram for various number of channels DWDM using hybrid EDFA-SOA (a) 1, (b)8 (c) 16 (d) 24 (e) 32

3.3 Performance Analysis on Hybrid EDFA-Raman

The lengths of the optical amplifiers were fixed at 5km and 40km for EDFA and Raman respectively. Figure 5 exhibits the maximum Q-factor of hybrid EDFA-Raman at channel 1,8, 16, 24 and 32. In contrary with hybrid EDFA-SOA, the appointment of EDFA-Raman resulted the best transmission signal received at Channel 1 with Q_{factor}=43.0579 a.u. Channel 16 experienced more losses than other channels in which the value of Q_{factor} was obtained as 39.3266 a.u. However, the hybrid EDFA-Raman produced better stability than EDFA-SOA where the received signals were fluctuated within ±3.73 a.u. The minimum BER value at channels 1,8,16,24 and 32 shows zero reading since it depends on the co-propagating pump power. The amount of Four Wave Mixing (FWM)-generated crosstalk exceeded the permissible value and deteriorated the value of the minimum BER. Figure 6 depicts the BER pattern of hybrid EDFA-RAMAN at selected channels. In comparison with EDFA-SOA, the BER

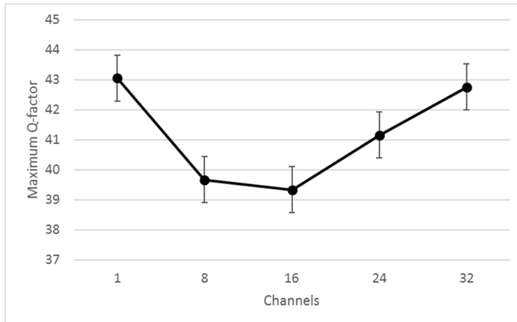
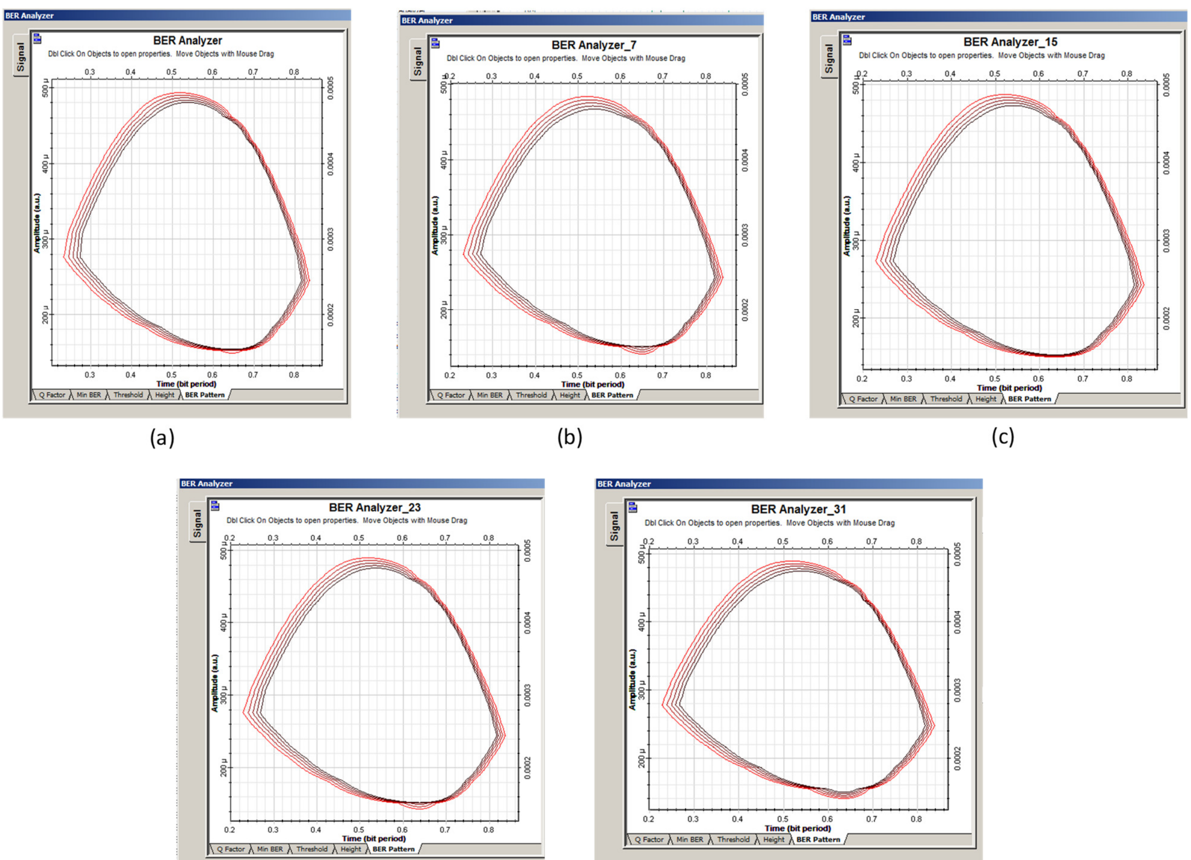


Fig. 5. Maximum Q-factor for various channels of DWDM using hybrid EDFA-RAMAN



(a) (b) (c)

(d) (e)

Fig. 6. BER pattern for various channels of DWDM using hybrid EDFA-RAMAN (a) Channel 1, (b) Channel 8, (c) Channel 16, (d) Channel 24 and (e) Channel 32

pattern at all channels exhibited similar patterns with smaller contour. The contour represented the presence of nonlinear effect such as noise and distortion experienced by the system during signal transmission. The bigger the contour size, the higher the distortion. Figure 7 displays the eye diagram at the receiver as hybrid EDFA-RAMAN were employed in the system. Channel 1 owned the widest opening eye diagram due to its highest Q-factor value in comparison with other channels. This situation demonstrated the occurrence of minimum signal distortion which led to excellent quality of data transmission. Channel 16 experienced lowest Q-factor which demonstrate the poorest signal quality among other channels. Nevertheless, note that the eye pattern of EDFA-Raman was apparently wider than EDFA-SOA which proved the significant contribution of hybrid EDFA-Raman in enhancing the optical performance of DWM network.

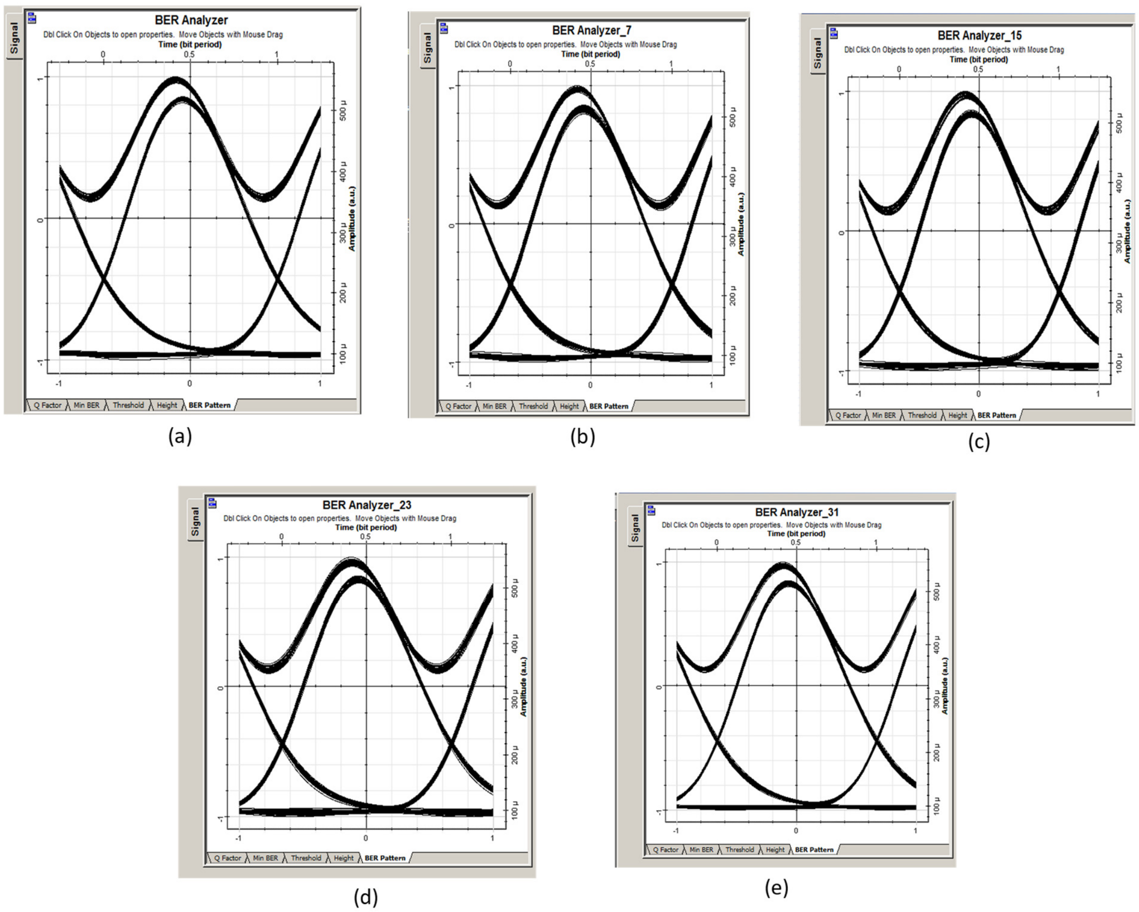


Fig. 7. Eye diagram for various channels of DWDM using hybrid EDFA-RAMAN (a) Channel 1, (b) Channel 8, (c) Channel 16, (d) Channel 24 and (e) Channel 32

3.4 Performance Analysis on Hybrid Raman-SOA

Length of RAMAN fiber was fixed at 40km. The value of injection current in SOA remained at its optimal value which was I=0.2 A. Figure 8 portrays the maximum Q-factor of as hybrid RAMAN-SOA was integrated in the optical network system. In general, it can be concluded that the signal amplification was slightly smaller in comparison with EDFA-Raman. However, the employment of Raman-SOA was much better than EDFA-SOA in which the signal was successfully amplified up to 86.63%. The signal was excellently transmitted to receiver at channel 32 by considering highest value of Q-factor which was 39.8011 a.u. Channel 16 experienced large signal attenuation represented by Q factor value of 31.7521 a.u. In a stability perspective, this integrated hybrid Raman-SOA was less stable than EDFA-Raman where the Q-factor values of selected channels were fluctuated about ±8.049 a.u of deviation. The BER values at channels 1 and 32 indicated zero reading meanwhile at channel 8, 16 and 24; the BER values were obtained as 3.25134×10^{-282}, 1.42×10^{-221} and 4.94×10^{-264} respectively. Figure 9 displays the BER pattern of received signal by employing hybrid RAMAN-SOA.

In general, all channels produced similar patterns. The size of contour was slightly larger than EDFA-Raman, yet obviously smaller than EDFA-SOA which demonstrated the moderate performance of this DWDM network. Figure 10 shows the eye diagram of hybrid RAMAN-SOA for channel 1, 8, 16, 24 and 32 respectively to identify the factors that limit the data transmission. It was obviously seen that channel 32 has the widest opening and the smoothest eye diagram as it has the highest value for Q-factor in comparison with other channels. This means that it has the lowest distortion and has better quality in transmitting the signal.

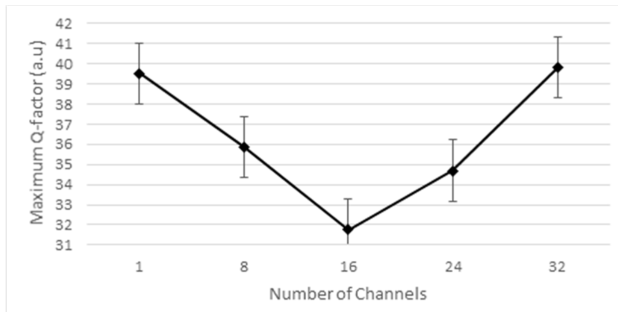


Fig. 8. Relationship between maximum Q-factor and various channels of DWDM using hybrid RAMAN-SOA (a) Channel 1, (b) Channel 8, (c) Channel 16, (d) Channel 24 (e) Channel 32

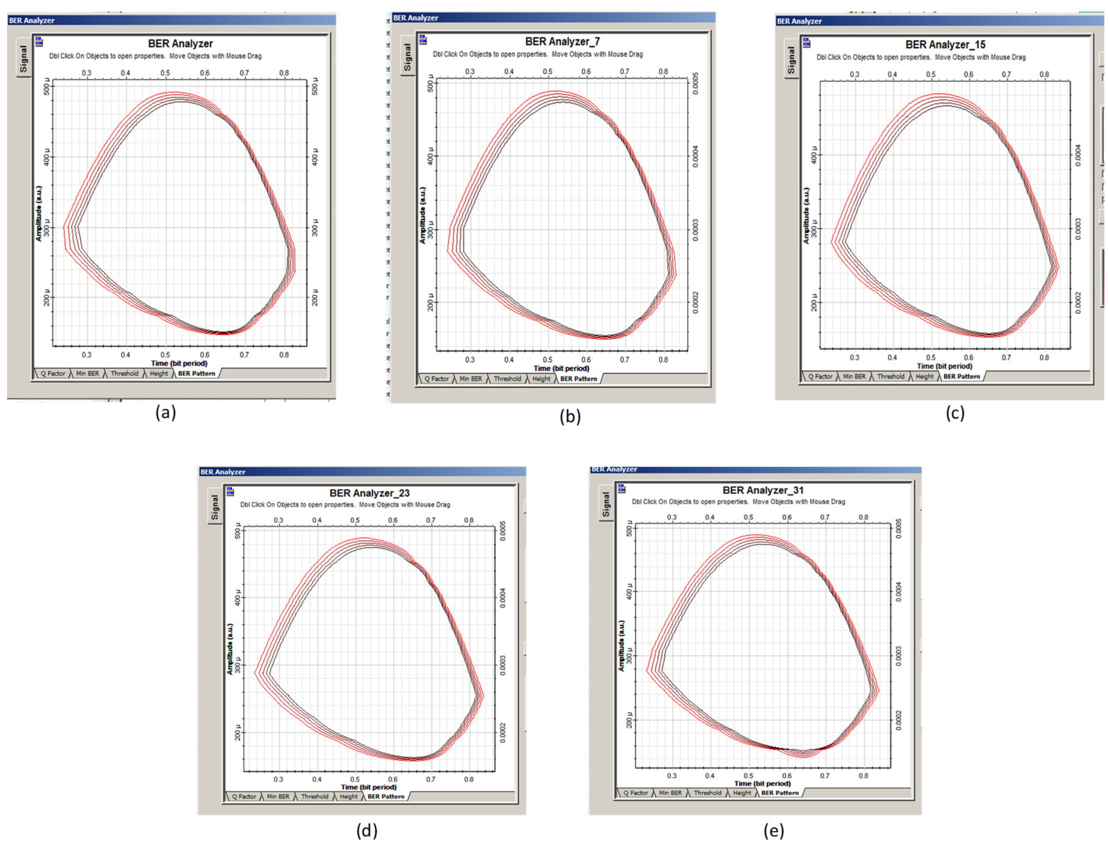


Fig. 9. BER pattern for 32 channels DWDM using hybrid RAMAN-SOA Maximum Q-factor for various channels of DWDM using hybrid RAMAN-SOA (a) Channel 1, (b) Channel 8, (c) Channel 16, (d) Channel 24 and (e) Channel 32

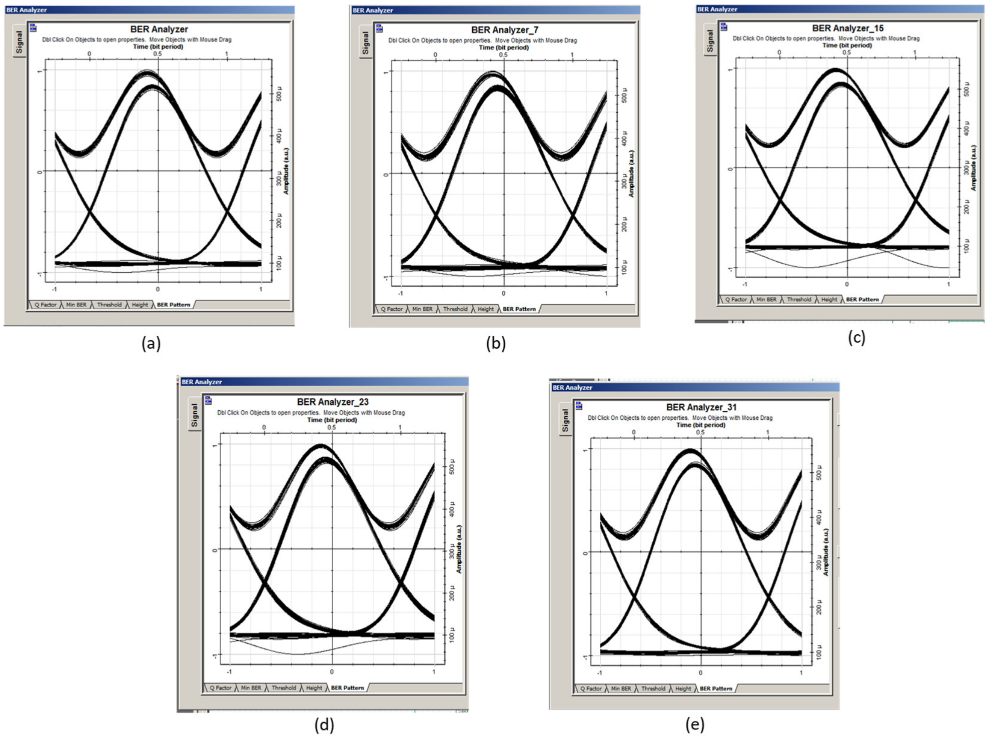


Fig. 10. Eye diagram for various channels of DWDM using hybrid RAMAN-SOA (a) Channel 1, (b) Channel 8, (c) Channel 16, (d) Channel 24 and (e) Channel 32

3.5 Optimization of 32 Channels DWDM in Optical Parametric Amplifiers between Hybrid EDFA-SOA, EDFA-Raman and Raman-SOA

Figure 11 illustrates the maximum Q-factor of hybrid EDFA-SOA, EDFA-Raman and Raman-SOA. It was apparently observed that hybrid EDFA-RAMAN experienced the highest Q-factor among the others. The employment of EDFA-Raman able to optimize the received signal in which the nonlinear effect such as noise and distortion was successfully reduced. This result indicated better quality of signal transmission of EDFA-Raman compared to EDFA-SOA and Raman-SOA.

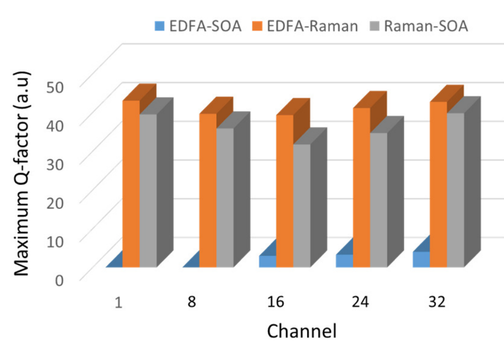


Fig. 11. Relationship between maximum Q-factor (a.u) and number of channels for hybrid EDFA-SOA, EDFA-RAMAN and RAMAN-SOA

The integration of hybrid EDFA-SOA in optical network is not recommended due to its extremely low Q-factor which demonstrated a low quality of received signal. We believe that the employment of SOA produced the largest amount of amplified spontaneous emission (ASE) which possibly can cause serious signal distortions.

Figure 12 demonstrates the stability of received signal for various optical networks integrated with hybrid EDFA-SOA, EDFA Raman and Raman-SOA. This analysis was performed by taking into account the deviation between smallest value of maximum Q factor and the largest one for all channels. An excellent optical networks should have a stable output signal represented by almost similar Q-factor values at each channels which results nearly zero deviation. Obviously, the employment of EDFA-Raman resulted smaller deviation which indicated that all channels received similar strength of signal. The integration of EDFA-SOA and Raman-SOA displays less stability of optical system due to the signal received for each channels was obviously fluctuated.

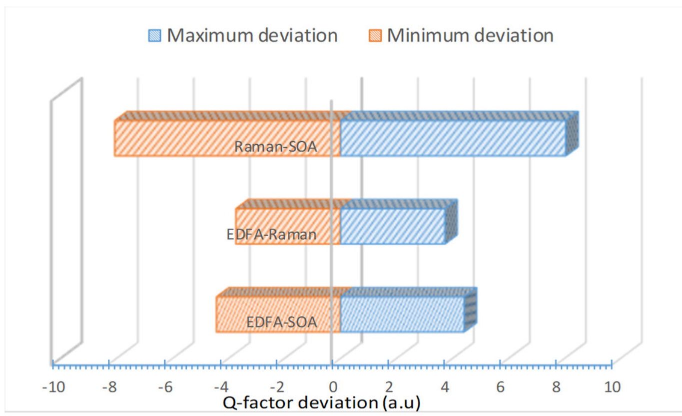


Fig. 12. Analyses on received signal's stability at selected channels (1, 8, 16, 24 and 32) between EDFA-SOA, EDFA Raman and Raman-SOA

4. Conclusions

In conclusions, the integration of EDFA-Raman in 32 channels DWDM optical network indicated excellence signals amplification at the receiver part. Surprisingly, the output signals for three types of hybrid configuration namely EDFA-SOA, EDFA-Raman and Raman-SOA were not uniformly received at the receiver part. Stability analyses proved that the employment of EDFA-Raman able to produce better signal stability with ±3.73 a.u of Q-factors deviation throughout all channels.

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References

[1] Tibuleac, Sorin, and Mark Filer. "Transmission impairments in DWDM networks with reconfigurable optical add-drop multiplexers." *Journal of Lightwave Technology* 28, no. 4 (2010): 557-568.
[2] Sahoo, Satyajit, K. V. Kiran, V. Kumar, D. Yadav, N. K. Barpanda, and Santos Kumar Das. "Quality Analysis in Phase Modulated Radio over Fiber in WDM/DWDM Network." *Journal of Optical Communications* 38, no. 2 (2017): 153-159.

[3] Santos, João R., António Eira, and João Pires. "A Heuristic Algorithm for Designing OTN Over Flexi-ble-Grid DWDM Networks." *Journal of Communications* 12, no. 9 (2017).
[4] Keiser, Gerd. Optical fiber communications. McGraw-Hill Education, 2015.
[5] Pelegrina-Bonilla, Gabriel, Katharina Hausmann, Hakan Sayinc, Uwe Morgner, Jörg Neumann, and Dietmar Kracht. "Analysis of the modal evolution in fused-type mode-selective fiber couplers." *Optics express* 23, no. 18 (2015): 22977-22990.
[6] Mukhtar, Wan Maisarah, P. Susthitha Menon, and Sahbudin Shaari. "Effect of taper angle of the optical fiber microprobe in power collection." In *Advanced Materials Research*, vol. 403, pp. 3387-3391. Trans Tech Publications, 2012.
[7] Mukhtar, Wan Maisarah, Sahbudin Shaari, P. Susthitha Menon, and Abang Annuar Ehsan. "Analysis of biconical taper geometries to the transmission losses in optical microfibers." *Optoelectronics and Advanced Materials, Rapid Communications* 6, no. 11-12 (2012): 988-992.
[8] Zhu, Zhonghua, and Shan Zhong. "OvS: A Distributed and WDM/SDM Enabled Optical Switching Fabric for Intra-Data Center Networking." In *Photonics in Switching*, pp. PW3B-2. Optical Society of America, 2014.
[9] Kazama, Takushi, Takeshi Umeki, Masashi Abe, Koji Enbutsu, Yutaka Miyamoto, and Hirokazu Takenouchi. "Low-parametric-crosstalk phase-sensitive amplifier for guard-band-less DWDM signal using PPLN waveguides." *Journal of Lightwave Technology* 35, no. 4 (2017): 755-761.
[10] Kour, Mandeep, Anu Sheetal, and S. B. Rana. "Performance Analysis of 32× 10 Gb/s DWDM Optical System using YDFA for Different Channels Spacing." *International Journal of Innovations in Engineering and Technology (IJIET)* 5 (2015).
[11] Saris, N. N. H, Hamzah, A. and Ambran, S. "Investigation on Gain Improvement of Erbium Doped Fiber Amplifier (EDFA) By Using Dual Pumped Double Pass Scheme." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 7, no. 1 (2017): 11-18.
[12] Hamzah, A., N. N. A. Azrin, and N. N. H. Saris. "Flat-gain and Wideband EDFA by using Dual Stage Amplifier Technique." *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)* 10, no. 2-6 (2018): 25-29.
[13] Patni, Amit, and Durgesh Kumar. "Simulation of gain flattened 32 channels EDFA-DWDM optical system." In *Recent Advances and Innovations in Engineering (ICRAIE), 2016 International Conference on*, pp. 1-4. IEEE, 2016.
[14] Zhang, Lei, Huawei Jiang, Xuezong Yang, Xijia Gu, and Yan Feng. "High-power single-frequency 1336 nm Raman fiber amplifier." *Journal of Lightwave Technology* 34, no. 21 (2016): 4907-4911.
[15] Chen, Yubin, Zefeng Wang, Zhixian Li, Wei Huang, Xiaoming Xi, and Qisheng Lu. "Ultra-efficient Raman amplifier in methane-filled hollow-core fiber operating at 1.5 µm." *Optics express* 25, no. 17 (2017): 20944-20949.
[16] Freude, Wolfgang, René Schmogrow, Bernd Nebendahl, Marcus Winter, Arne Josten, David Hillerkuss, Swen Koenig et al. "Quality metrics for optical signals: eye diagram, Q-factor, OSNR, EVM and BER." In *Transparent Optical Networks (ICTON), 2012 14th International Conference on*, pp. 1-4. IEEE, 2012.
[17] Singh, Simranjit, and R. S. Kaler. "Performance evaluation of 64× 10 Gbps and 96× 10 Gbps DWDM system with hybrid optical amplifier for different modulation formats." *Optik-International Journal for Light and Electron Optics* 123, no. 24 (2012): 2199-2203.
[18] Khan, F. N., Alan Pak Tao Lau, Zhaohui Li, Chao Lu, and P. K. A. Wai. "OSNR monitoring for RZ-DQPSK systems using half-symbol delay-tap sampling technique." *IEEE Photonics Technology Letters* 22, no. 11 (2010): 823-825.
[19] Argyris, Nikolaos, Stefanos Dris, Christos Spatharakis, and Hercules Avramopoulos. "High performance carrier phase recovery for coherent optical QAM." In *Optical Fiber Communication Conference*, pp. W1E-1. Optical Society of America, 2015.