Semiconductor Optical Amplifier for Optical Channel Capacity Improvement Based on Cross-Phase Modulation

Mohammad Syuhaimi Ab-Rahman, Abdul Hameed Almabrok Swedan
Department of Electrical, Electronic & System Engineering,
Faculty of Engineering and Built Environment,
Uinversiti Kebangsaan Malaysia.
aswsw2002@yahoo.com

***Abstract*—A tremendous increasing in telecommunication networks proportional to the variety and growth of data exchange services resulted in a diversity of configuration limitation in access networks. This paper presents one of nonlinearity behaviour of semiconductor optical amplifier identified as cross gain modulation that allows copying the same data from one wavelength to many wavelengths, which leads to increase the number of access points at same speed. 10 Gb/s One to two cross phase modulation wavelength conversion is discussed using semiconductor optical amplifier Mach–Zehnder interferometer at optical network unit with 64 splitting ratios. The configuration can convert a modulated signal of specific pump wavelength to continuous wavelength 1556 nm and 1558 nm (probes' wavelength) with two nm spacing to reduce four-wave mixing effect. The influence of data format on the system performance verified that the system able to implement for different data format regarding power levels of pump and probes, interesting the return to zero formats give better performance than non-return to zero. Another important finding was that the possibility of up and down conversion. The outcomes of conversion efficiency are in agreement with the literature and obtained good values for up and down conversion.**

***Index Terms*—Cross-Phase Modulation; Multi-Wavelength Conversion; Optical Network Capacity; Semiconductor Optical Amplifier.**

I. Introduction

New services demand for different types of data multimedia and internet traffic have been growing, such as Smart devices and cloud services. Recurrently, network vendors are required to set up new access networks for all the lines to user's locations to deal with high bandwidth requirements. As demands increase, various optical network units (ONU) has been exhausted fulfill the data capacity required. Thus upgrade data rate of ONU and other standards are needed [1-2]. According to ITU-T G.989.1, more than 10 Gb/s bitrate per upstream channel within 20 km range are needed for next generation passive optical networks (PON) with a minimum of 1:64 splitter [3]. Furthermore, Akamai's state of internet report 'Q3 and Q4' has reported that the Average Connection Speed for the ranked first countries per regions, USA, Japan and Sweden increased from (12.6, 15 and 17.4 Mb/s)to (14.2, 17.4 and 19.1 Mb/s) respectively [4].

There are several proposals have been testified to offer both vendors and users' demand. Among the solutions have been introduced were optical amplifiers Erbium doped fiber, Raman optical amplifier and Semiconductor optical amplifier (SOA), which used to increase system power budget[5-9]. SOA works as an amplifier with a gain range 20 to 25 dB or as a nonlinear device that can function for optical data signal processing such as switching, optical gates and optical wavelength converter (OWC) [10-17].

The main portion of multi-wavelength transceiver networks are OWC, which can be utilized in different configurations. i.e. four-wave mixing (FWM), cross gain modulation (XGM) and cross phase modulation (XPM) [18-21]. In the past several configurations represented the wavelength conversion at optical line terminal (OLT) provide multi-channels, but each channel has to be amplified [22-25], on the other hand, colorless ONU and assisted light usually used for up streams transmission [26-30].

For the time being, the investigated studies in terms of the wavelength conversion do not clarify the position impact of the SOA device. There are many papers present solutions, methods and configurations dealing with this issue. One to two XGM-WC configuration investigated in [31].the authors have reported improvement regarding to the total number of users. However, the data of converted channels was inverted in which more processes are needed. The bandwidth limitations of existing networks for the end user requirement encouraged this work to develop their standards, in order to cope up the demands. In this work 1 to 2 XPM based on semiconductor optical amplifier Mach–Zehnder interferometer (SOA-MZI) structure that offers non-inverted data for converted channels are demonstrated.

This article focuses on the XPM based on SOA as a nonlinear medium, which can generate same data sequences for converted channels and operate at high data rate 10 Gb/s or more. The architecture of 1 to 2 XPM at ONU using two-semiconductor optical amplifier integrated with Mach zander Interferometer (SOA-MZI) proposed and demonstrated to obtain (1:64) splitting ratio for the non-inverted channels, with a good conversion efficiency and maximum Q values, for both (up & down) conversion under the specified operating conditions. The scheme verified by applying one modulated pump signal and two continues wave laser as probes. The suggested configuration is simple to implement, and it can be efficient for both RZ and NRZ data format. Furthermore, the impact of pump wavelength over 14nm range for up and down conversion was analyzed.

The paper is organized as follow; the system configuration and the operational principle of one to two XPM using SOA-MZI introduced in section 2. The mathematical background is reviewed in section 3, which describes the conversion efficiency for converted channels at ONU, achieving wavelength conversion status and support 1:64 splitting ratio for each channel. Section 4 discusses the impact of different data format return to zero (RZ) and non-return to zero (NRZ). Furthermore, the effect of pump wavelength is demonstrated in terms of Q-values. In addition, the CE is measured using (1541 nm, 1553 nm) and (1561 nm, 1562 nm) for up and down conversion respectively. Finally, the overall system performance is summarized in section 5.

II. System Configuration and Operational Principle

A scheme with the speed of 10 Gb/s multi-wavelength conversion implemented by the SOA-MZI full architecture is shown in Figure 1. The system demonstrates the possibility of one-to-two wavelength converter based on cross-gain modulation conduct of semiconductor optical amplifier worked as nonlinear module. The architecture consists of two optical power sources; the first is modulated pump light with a power range of 5 dBm to -3 dBm, while the second one is the two continuous wavelengths (CW) probes 1556 nm and 1558 nm range 3 dBm to -5 dBm.

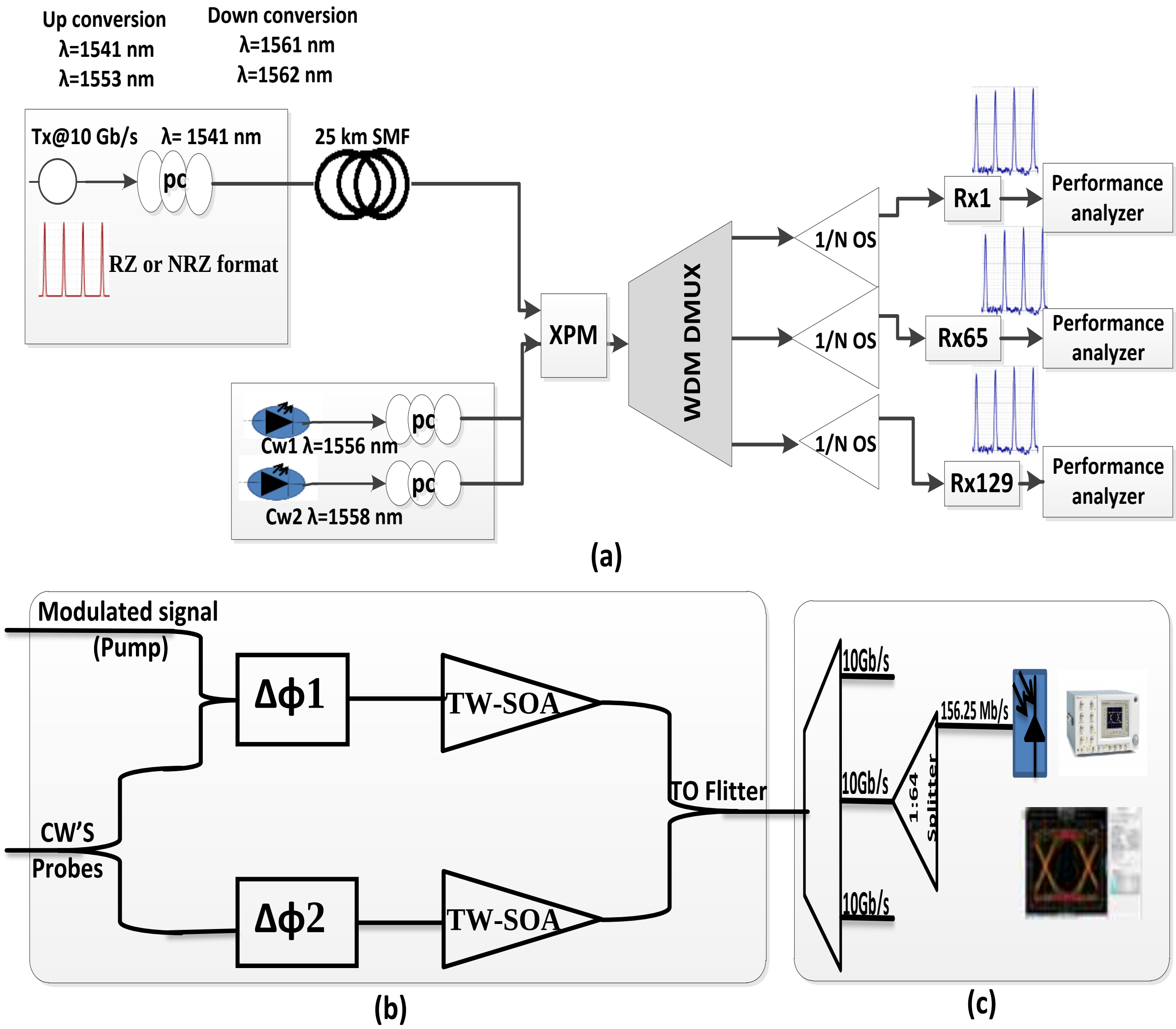

Figure 1: System set up (a) Full configuration diagram (b) XPM block (SOA-MZI) (c) Receiver block

The modulated light transmitted along 25 Km single mode fiber, then pumped to XPM block with CW's light. A couple of SOA after the optical phase shift connected to govern the XPM process. At the output of the SOA-MZI, the spectrum is optically filtered by demultiplexer to separate original pump wavelength and converted channels, after that the power of each wavelength is divided into 64 routes using an optical splitter, PIN photodiode used to detect data before it tested by bit error rate analyzer. XPM in nonlinear medium produce the optical phase shift of the light due to interaction with another beam, exactly a Kerr medium. Particularly, the cross phase modulation can represent a refractive index change that produces a phase shift of probe light. The process considered simple: the modulated pump at a particular wavelength (λ_{pump}) after 25 km SMF added to the XPM block at upper arm. After that mixed with CW's light at (1556 nm and 1558 nm) wavelengths injected into configuration at the lower arm that described in Figure 1.(b). The converter process depending on SOA's design parameters values, such as optical power (pump power and probes power). On the other hand, it is governed by the bias current. The two electric current (I_{SOA1}) and (I_{SOA2}) optimized to 300 mA and 250 mA in the same order, and the optical phase shifter φ_1 and φ_2 adjusted to provide non-inverted data sequence for probes wavelengths. The setup used to obtain three different objectives, firstly, to identify the impact of different data format on system performance regarding the non-return to zero (NRZ) and return to zero (RZ) of pump wavelength has considered. Then to investigate (up and down) conversion in the range of 14 nm of pump wavelength, 1540 nm to 1553 nm up-conversion and 1559 nm to 1572 nm down conversion. Finally, the conversion efficiency of the RZ data format for up and down conversion figured out.

III. THEORETICAL BACKGROUND

The cross-phase modulation phenomenon (XPM) is one of a nonlinear effect in semiconductor amplifier. It is related to the variation of the refractive index caused by an optical signal (defined as pump signal), which influences the phase of one or multiple optical signals (probes) transmitting at the same time in the SOA configuration. Table (1) show the parameters used in this proposal.

This research considers the modulated pump power intensity with a different data format Gaussian optical pulse, NRZ and RZ. In the first test, the pump wavelength 1541 nm is used. After that, the numbers of 28 wavelengths were used as a pump to investigate its effect. Also in the third measurements 1541nm,1553 nm,1561 nm and 1562 nm were used for up and down-conversion validation. The two probes 1556 nm and 1558 nm are used to provide converted channels. Due to the change of photon and carrier density along the SOA that can be represented by rate equation.

Table 1
Parameters Used in This Architecture

Symbol	Parameter	System Parameters Values		
		XPM		[31]XGM
λ_{pump}	pump wavelength	Up-conversion 1541 nm,1553 nm Down-conversion 1561 nm,1562 nm		1541nm
P_{pump}	Pump power range	5 to -3 dBm		-6 to 3 dBm
λ_{probe}	Probe wavelength	1556 nm&1558 nm		1554 nm &1558 nm
P_{probe}	Probes power	3 to -5 dBm		0 dBm
		SOA1	SOA2	
Ic	Bais current	300 mA	250 mA	200 mA
L	Active region length	600 µm	600 µm	600 µm
Γ	Confinement factor	0.45	0.45	0.45

Connelly [32], Presented the numerical model, which was adopted by opti.system© software, that used to implement and prove the objectives of the proposed system. The carrier density rate-equation was given by:

$$\frac{dN_i(z)}{dt} = \frac{I}{edLW} - R(N_i(z)) - \frac{\Gamma}{hdW} \times \left\{ \sum_{k=1}^{Ns} \frac{g[N_i(z), v_k]}{v_k} p_k(z,t) \right\} - \frac{2\Gamma}{hdW} \left\{ \sum_{j=0}^{N_{m-1}} \frac{g[N_i(z), v_j] K_j}{v_j} \times \left[P_{ASE}^{+}(N(Z)) + P_{ASE}^{-}(N(Z)) \right] \right\} \tag{1}$$

where L is the length, d is the thickness and W is the width of the active region. I is the bias current to the amplifier, e is electron charge, h is the plank's constant. Γ is the confinement factor, Pk determines the power of the different lights in SOA, and the subscript k = s, p, a, stands for signal, probe and assist light similar ordering. $P^{+}ASE$ and $P^{-}ASE$ represent the noise power for the forward and backward direction, R is the radiative and non-radiative carrier recombination rates. Furthermore, K_j is the filter factor.

To demonstrate the objectives of this article measurement of Q-factor and conversion efficiency considered and analyzed.

A. The Q-Factor

The Q-Factor is effective measurement tool to study the overall system performance in optical network systems [33]. The performance corresponding to Q value equal 6 or more parallel to bit error rate 10^{-9}. It defined as

$$Q = \frac{H_L - L_L}{\sigma_H + \sigma_L} \tag{2}$$

where the parameters are: H_L is the average high power level, L_L is the average low power level, and σ_H and σ_L are the high and low power level standard deviations in that order.

B. Conversion Efficiency

In this work, the conversion efficiency used to evaluate the WC of the suggested configuration for up - down conversion. Here the CE is the measure of the converted power of each probe (P_{probe} out) to the power of input signal (P_{signal} in), which calculated using Equation (3) [34].

$$\eta = \log \frac{P_{out}(\lambda_{conv})}{P_{in}(\lambda_{pump})} \tag{3}$$

IV. RESULT AND DISCUSSION

The configuration of the proposed model deliberated in section (II). This paper examines the performance of 1-to-2 XPM using SOA-MZI architecture, at 1541 nm pump, 1556 nm and 1558 nm probes. Three cases investigated and considered to prove the wavelength conversion process. The power effect of pump and probes for different data format are analyzed, and then the best values of probes power are selected to achieve the highest Q values. The impact of pump's wavelength on the signal quality for up and down conversion using RZ data format then is investigated. Thirdly, the conversion efficiency is evaluated to determine the effectiveness of conversion operation of RZ data format, for two cases. The wavelengths 1541 nm and 1553 nm for up-conversion, and 1561 nm and 1562 nm represents down-conversion analysis.

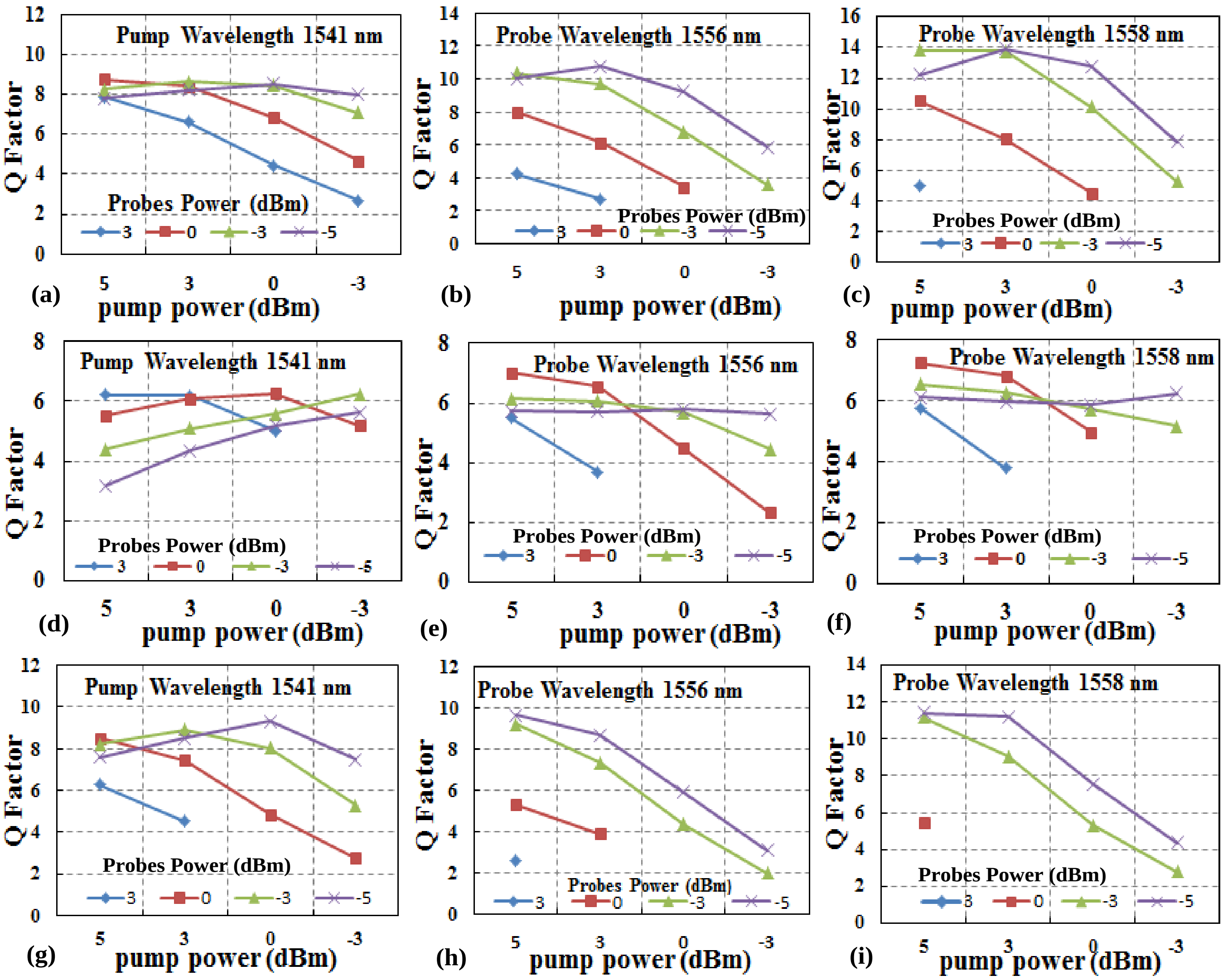

Figure 2: Q-factor variation due to changing the probe power at different pump powers for 1556 nm, 1558nm probes and1541nm pump wavelengths. (a, b and c) Gaussian pulse optical signal, (d, e and f) NRZ format and (g, h and i) RZ format

A. Impact of data format on the system performance

To investigate the effect of data format on the system performance, the Q-factor measured for various probes power at different pump power.

The results in Figure 2 Indicated that the Q values have different effects for pump and probes wavelength. Using Gaussian signal at 0 dBm recorded 8.45, 6.14 and 8.08 for 1541nm, 1556nm and 1558nm in the same order. However, for the NRZ the values are 6.27, 4.48 and 4.97 for 1541 nm, 1556 nm and 1558 nm respectively. Besides, for RZ only 1541nm is noted 4.84.but

As well, the data format has highly influenced by different values of probes power. It is impossible to provide all WC at 3 dBm probes power for both original and converted channels of three considered data format; For example, at 1558 nm there is no result at all values of pump power for RZ data. Meanwhile, the same wavelength at -5 dBm of the probe power three values of the pump power 5, 3 and 0 dBm achieved the acceptable result of Q-values 11.43, 11.22 and 7.54. As well, for the Gaussian optical pulse data under the same condition of the probes power at -5 dBm of all pump power levels the Q-values are in the suitable range. Inversely, for NRZ it is clear that the Q-values are lower than Other two data format cases, and the WC can be implemented at (3 dBm pump power) matched to (0 dBm probes power) for pump and probes wavelength.

Based on the result, applying the Gaussian pulse or RZ format the best power values of the pump and probes are 3 dBm and -5 dBm accordingly. On the other hand, for NRZ data format the appropriate power values are 0 dBm probes and 3 dBm pump.

To clarify the influence of data format, the model implemented with the results from the previous measurement. Figure 3 describes the Q- values changes regarding different data format for various pump values at optimum probes power.

As can be seen from Figure 3, it is obvious that for the Gaussian optical signal, the WC can be used at three pump power values 5, 3 and 0 dBm. However, for RZ format two values of pump power 5 and 3 dBm can present WC process for all frequencies. Meanwhile, for NRZ format the WC operation is only feasible for the 3 dBm value of the pump power. Additionally, in Comparison between RZ and NRZ data format, the results show that the values of Q-factor for RZ are higher than NRZ format for all wavelengths. In conclusion, for the proposed configuration is better to use RZ data format at the specified power values of pump and probes, to be more beneficial for applications in communication networks.

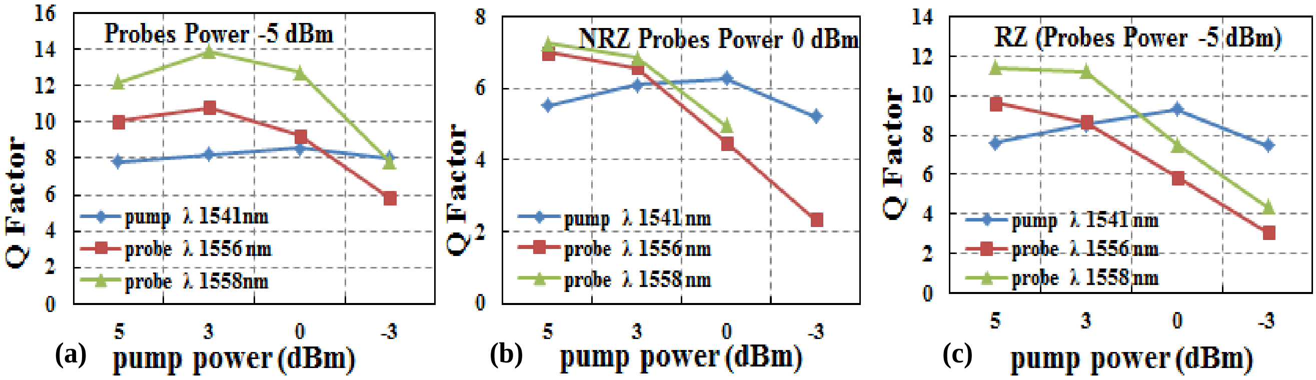

Figure 3: Q-factor values as a function of the probes power at different pump powers, for 1556 nm, 1558nm probes and1541nm pump wavelengths. (a) Gaussian pulse optical signal (b) NRZ format. (c) RZ format

B. Influence of pump wavelength on overall performance using RZ data format

The pump wavelength is one of the most important factors that need to take into account in studying the wavelength converter system. The impact of pump's wavelength up and down conversion is illustrated in Figure 4.

Figure 4 depicts the range of 28 nm wavelengths, 14 nm up-conversion and 14 nm down-conversion, to provide 10 Gb/s 1 to 2 XPM WC for RZ data format at ONU with 25 km SMF. According to these findings, we can infer that six pump wavelengths able to implement up- conversion for both 1556 nm and 1558 nm, while four pump wavelengths capable of complete down-conversion operation for two probes. However, the Q values for acceptable wavelengths indicated that there is no significance difference for up and down conversion analysis.

To distinguish, the acceptable wavelengths 1540 nm, 1541 nm, 1542 nm, 1551 nm, 1552 nm and 1553 nm for up-conversion, while for the down-conversion the successes wavelengths are 1559 nm, 1561 nm, 1562 nm, 1565 nm. The rest of the wavelengths need different optimization to be applied for similar function, because at least one of them fails to get accepted Q value. Especially, the wavelengths which falls in the circles area (no result) as shown in Figure 4 a &b. For example; when the 1545 nm pump is used the probe wavelength 1558 nm get the highest value about 14, but the probe wavelength 1556 nm drop to no result area, the same thing is occurred with 1568 nm in Figure 4(b). The reason of missing wavelengths could be due to FWM effect, thus optimization the SOA is needed for every comb of wavelengths to prove XPM operation.

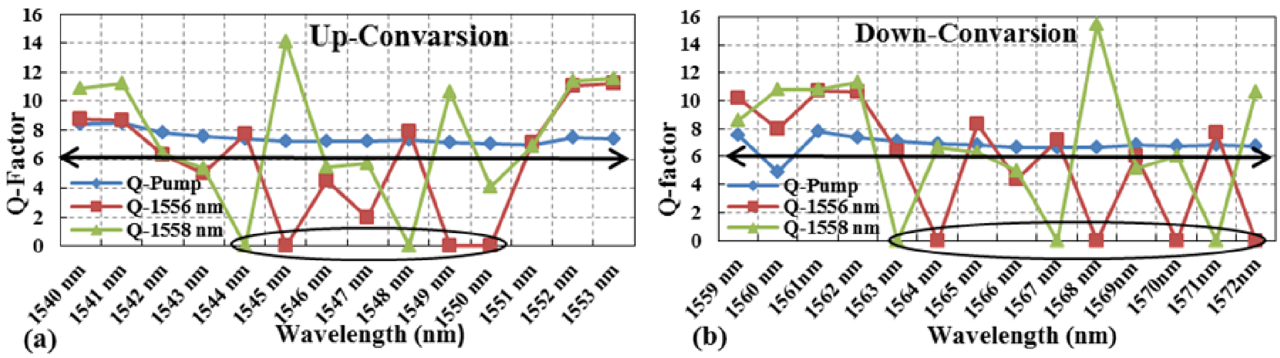

Figure 4: The Q-values changes as a function of the pump wavelengths, for 1556 nm, 1558 nm probes and 1541 nm pump wavelengths. (a) up-conversion (b) down-conversion.

C. Effect of probes power on conversion efficiency

The optical wavelength converter method can verify through the measurements of conversion efficiency. The outcomes of CE variation related to probes power change displayed in Figure 5. To distinguish between these two possibilities, Four-pump wavelengths 1541 nm &1553 nm up-conversion and 1561 nm &1562 nm down conversion are considered. For all measurements, it is clear to see that the CE values for 1558 nm probe are better than the CE values of 1556 nm probe. In addition, when the two pump wavelengths are compared the results show the 1553 nm is more efficient than 1541 nm pump in up-conversion. Nevertheless, for the down-conversion can be noted that the 1561 nm achieves a better result than 1562 nm. Consequently, the best wavelength can provide WC for this design is 1553 nm. Also, findings showed that the CE values inversely proportional to the probes power, which measured the highest at -5 dBm probe power. The values of the CE is found to be around 1.88 and 1.30 using the 1553 nm and 1562 nm respectively.

The configuration advantages, it's well known the SOA is small size and non-complex component due to this advantage is greatly suitable for integration with other devices. The system provides non-inverted data for converted channels, fewer stages needed to work as a capacity extender (over cross gain modulation requires more stage). The method principle is easily upgraded to a higher capacity system by further increasing the number of CW's laser creating the converted channels. In this work the total system capacity increased two times from 10 Gb/s to 30 Gb/s. The configuration can implement at 3 dBm to verify one to two XPM wavelength converter based on SOA-MZI integration at 25 km SMF with 1: 64 optical splitter. The modulated data from original channel at OLT can support 192 users with the downstream data rate is 156 Mb/s for each customer. For this bandwidth, it is interesting that implement the configuration on the network with ten channels the total system capacity will be 300 Gb/s and a total number of users 1920, which provide simple scalability system. Finally, the possible options of downstream bandwidth based on the splitting ratio for one channel system summarized in Table 2.

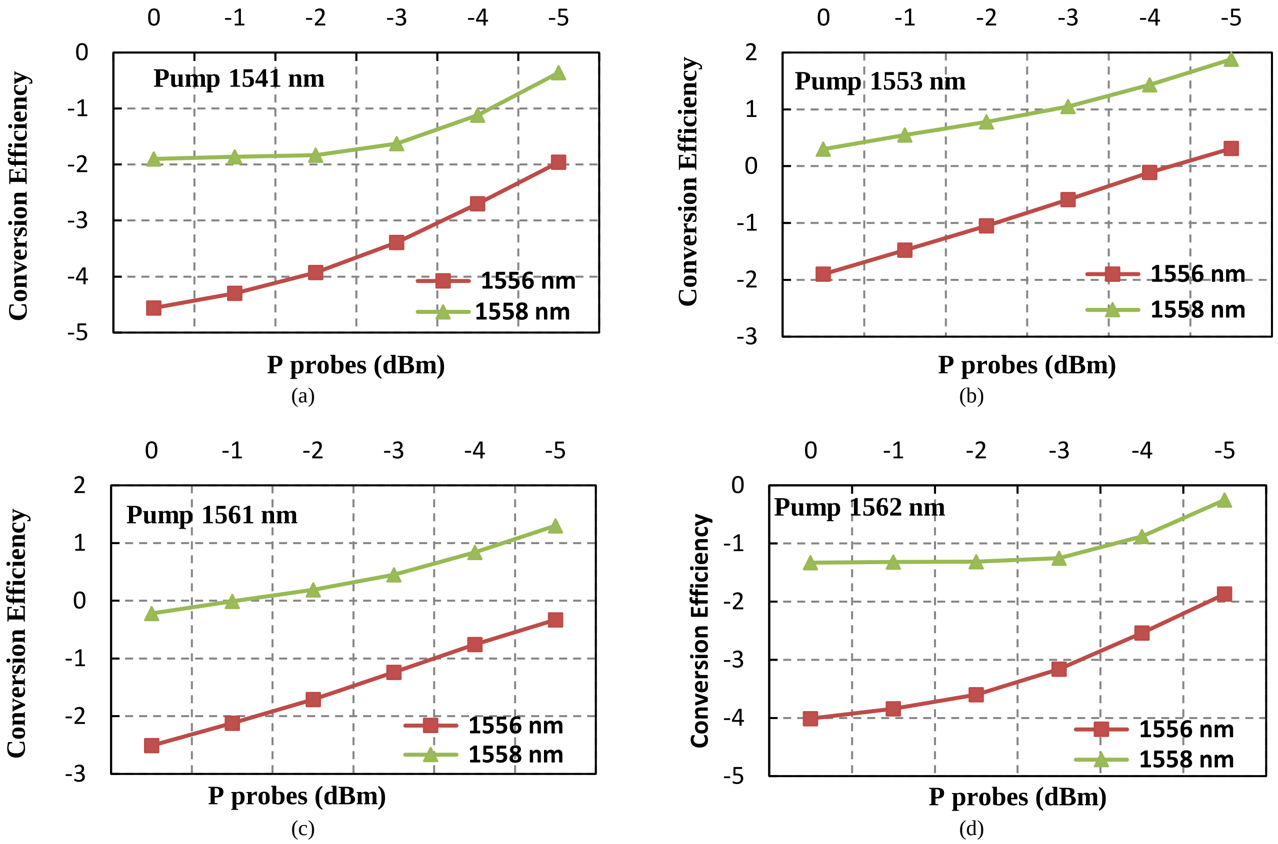

Figure 5: Conversion efficiency as a function of probes power change for 1556 and 1558nm wavelengths. (a) (b) 1541 nm &1553 nm up-conversion. (c) (d) 1561 nm &1562 nm down-conversion.

Table 2
Users Downstream Bandwidth Possibility of the Proposed System

Total System Capacity			Basic optical channel 10 Gb/s	Improved Basic &Converted Channels 30 Gb/s
Point to point		Bandwidth	10 Gb/s	3 to 3 10 Gb/s
		No.user	1	3
Point to multi-point	Splitting ratio 1:8	Bandwidth	1.25 Gb/s	1.25 Gb/s
		No.user	8	24
	1:16	Bandwidth	625 Mb/s	625 Mb/s
		No.user	16	48
	1:32	Bandwidth	312.5 Mb/s	312.5Mb/s
		No.user	32	96
	1:64	Bandwidth	156.25 Mb/s	156.25 Mb/s
		No.user	64	192

V. CONCLUSION

The presented study confirms previous findings and contributes additional evidence that proposed non-inverted data sequence directly using XPM. This paper investigates simultaneous double-wavelength conversion of modulated optical pump signal based on cross phase modulation through combined configuration of SOA-MZI. Simultaneous conversion on 1556 nm and 1558 nm with 2 nm spacing demonstrated for 10 Gb/s at ONU. The outcomes of this research provide the effect of data format on the MWC regarding the quality factor measurements. The scheme showed that the RZ format gives the better results over NRZ and a Gaussian-pulsed optical signal. Besides, in this investigation, the up and down conversion for RZ format obtained the Q values between 6.69 minimum and 11.59 maximum up-conversions. Whereas, for down conversion the Q values varying from 6.79 to 11.28. The research has also shown that the CE of the converted channels rises to more than -0.35 and 1.8 up-conversion of 1541 nm and 1553 nm pump to 1558 nm probe. While -0.25 and 1.30 for down conversion of 1561 nm and 1562 nm pump to 1558 nm probe. Besides the value in the worst case is -4.45 and -4.01 for up and down conversion of 1541 nm and 1562 nm pump to 1556 nm probe.

Further, increasing the number of CW'S source allows the designer to upgrade the capacity of networks as needed.

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