Cascaded wavelength converters using multiple pumping signals, covering all-optical (C-L) bands and achieving a remarkable bit-error rate

Mohamed I. Shehata and Osama A. Omer

Abstract— The aim of this work is to demonstrate the efficiency of a cascaded wavelength conversion by four-wave mixing technique in a commercial traveling wave semiconductor optical amplifier. A scheme of multiple cascaded wavelength converters spanning of 400 km for single-mode fibers is suggested. The proposed scheme differs from the conventional schemes as utilizing cascaded two commercial TW-SOA for each wavelength converter stage rather than using only one SOA in addition to Erbium-doped fiber amplifier (EDFA). This scheme overcomes the main problem appeared in the conventional schemes that suffer from the amplified spontaneous emission which considered as a noise that degrades optical signal to noise ratio of the converted signal. Based on the simulation results, bit-error-rate performance near 10^{-13} at 40 Gbit/s is achieved for five conversions up to 95 nm as a conversion range, covering C-L optical bands. A power penalty of 10.06 dB with a remarkable conversion efficiency of 98% (i.e. approximately free-error) is measured for overall system.

Keywords— Four-wave mixing, Cross gain modulation, Traveling wave semiconductor optical amplifier, Bit-error rate, Quality-factor, Conversion efficiency, Optical signal to noise ratio.

I. INTRODUCTION

Nowadays, All-optical wavelength conversion refers to the operation that consists of the transfer of the information carried from one wavelength channel to another wavelength channel in the optical domain. It is a key requirement for all optical networks because it is used to extend the degree of freedom to the wavelength domain. Moreover, All-optical wavelength conversion is also indispensable in future optical packet switching (OPS) networks to optimize the network performance metrics, such as packet loss rate and packet delay [1]. Also, it is very useful in the implementation of switches in wavelength division multiplexing (WDM) networks. In addition, it is crucial to lower the access blocking probability and therefore to increase the utilization efficiency of the network resources in wavelength routed optical networks. While a significant part of network design, routing and wavelength assignment depends on the availability and performance of wavelength converters.

Mohamed I. Shehata with the department of Electronics and Communication, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, South Valley, Aswan, Egypt (Corresponding Author; email: m.ismail34@aast.edu).

Osama A. Omer with the department of Electronics and Communication, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, South Valley, Aswan, Egypt (email: omer.osama@aswu.edu.eg).

Semiconductor Optical Amplifiers (SOAs) are considered the key components in all-optical signal processing functions required for WDM-DWDM networks. Some of these functions that utilize SOA nonlinearities are: 1) wavelength converters [2], 2) optical logic-gates [3], 3) bit-comparators [4], 4) all-optical-switching [1], 5) 3R regenerators [5] and 6) routing [6].

Nonlinearities in SOAs are principally caused by carrier density changes induced by the amplifier input signals. The four main types of nonlinearity are cross gain modulation (XGM), Cross phase modulation (XPM), Self-phase modulation (SPM) and Four-wave mixing (FWM) [7].

In order to demonstrate a wavelength converter with a remarkable performance, it is required to have wide conversion range, high conversion efficiency, high optical-signal-to noise ratio and low input power [8]. It is also preferable to achieve these specifications with a simple designs, configurations and setups.

Literatures indicate that multicasting based on XPM [9,10], looping utilizes SPM [11] and cascadability with FWM [12,13] are the preferable techniques that provide a remarkable wavelength converter performance over the O-S-C-L bands with nonlinearities in SOAs. Among all optical bands required to be covered by these techniques, C band still the most desirable band required to be covered in all SOA wavelength converter researches [14-16]. For all-optical multicasting with such large window hopping, the broadband wavelength conversion plays an important role in expanding the hopping range [17]. In particular, for SOAs XPM can provide large hop wavelength conversion, because of its effectiveness in a wide wavelength range [18]. Using a single SOA with a 1.3 µm gain band, broadband wavelength conversions to a much longer wavelength (1.55 µm) have been already demonstrated [19]. Although, multicasting has the previous advantages but it suffers from difficulty in converting into a much shorter wavelength, since the optical signal-to-noise ratio (OSNR) of the converted (probe) signal is drastically degraded [18].

Looping technique that utilizes SPM provide an acceptable SOA based wavelength conversion performance [20]. Single loop wavelength converter architecture provides significant merits like simple implementation and not requiring a high-speed short pulse laser or a clock recovery unit [11]. Unfortunately, this type of a simple wavelength converter has also been shown to be capable of a very limited number of repeated cascades, significantly restricting its use in a high-speed fiber transmission line [21]. These are partly compensated using the bi-directional data injection scheme and improves further on the performance but with the cost of adding large complexity to the looping technique [18, 22].

Cascading with FWM is another attractive technique that is used in achieving acceptable performance for all optical SOA based wavelength converter [12]. Cascading shows a little simpler designs than looping for the same wavelength range required to be covered [11, 23]. In addition, cascadability can cover effectively the shorter wavelength range than multicasting in a cost of increasing cascading stages [18, 24]. On the other hand FWM has the following merits over XPM & SPM as 1) utilizing ultra-fast intra-band nonlinearities in semiconductor optical amplifiers (SOAs), 2) independent of the bit rate, 3) modulation format transparency, 4) minimum degradation in system performance for a single SOA wavelength converter, and 5) None pulse broadening shape [13,25]. However, this technique suffers from low conversion efficiency, polarization sensitivity and the frequency shift dependent conversion efficiency [25]. In a conclusion, cascadadiability with FWM can be an effective choice in designing and testing high performance all optical SOA based wavelength converter as will be shown in this work.

L. Krzczanowicz and M. J. Connelly [26] utilize the merits of DQPSK in designing a 40 Gbit/s wavelength converter using bulk SOA-FWM over 1534.6 to 1536.6 nm. A parametric experimental study leads to the choice of bulk SOA gain with 21 dB, 10 dB saturation output power and 250 mA injection current to achieve an acceptable Q-factor operation.

An optimization process is then carried and results in improving the Q-factor to 10.25 dB. Two-fold cascade of SOA-based wavelength converters with 10 Gbit/s DPSK signals are demonstrated in [27].The wavelength is converted from λ_1=1550 nm to λ_2=1560nm at the first stage, and back to 1550 nm at the second stage. An error free wavelength conversion operation is obtained at about -31dBm of received optical power. The second-stage of the converter showed a negligible increase in power penalty.

In this work, a remarkable C-L optical bands SOA wavelength converter based on cascading with FWM technique is evaluated. A commercial Traveling-Wave Semiconductor Optical amplifier (TW-SOA) is used in simulations and optimizations. Optimization parametric process is carried targeting unique BER, remarkable conversion efficiency, acceptable converter complexity and acceptable injection current level. A comparison with related literatures that utilize the same technique and converter design is carried to prove the merits of this work.

This work is organized as follows: Section II provides a review on physics of FWM and the general SOA-based wavelength converter architecture using cascading with FWM. A detailed description for the simulation setup and its components/parameters is presented in section III. Results of the designed cascaded wavelength converter using commercial TW-SOA based on FWM nonlinearity technique and a comparison between our work and other related literatures are discussed in section IV. Finally, a conclusion of this work is stated in section V.

II. THE MULTIPLE STAGES SOA-BASED WAVELENGTH CONVERTER

Figure 1 is a schematic diagram that shows four-wave mixing in the frequency domain. It can be seen that the light before launching, sandwiching the two pumping waves in the frequency domain, is called the probe light (or signal light). The idler frequency (f_{idler}) may then be determined by:

$$f_{idler} = 2\, f_p - f_{probe} \tag{1}$$

Where: (f_p) is the frequency of the degenerated pumping wave [28, 29]. This condition is called the frequency phase-matching condition and will be a key concept for the five wavelength conversion stages as shown in Fig. 2.

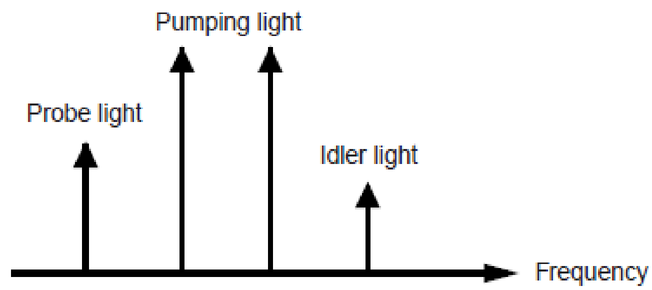

Fig. 1 Schematic of four-wave mixing in the frequency domain for two-channel pump wave

Figure 2 illustrates a general block diagram for the proposed five stages SOA-based wavelength converter that utilizes FWM.

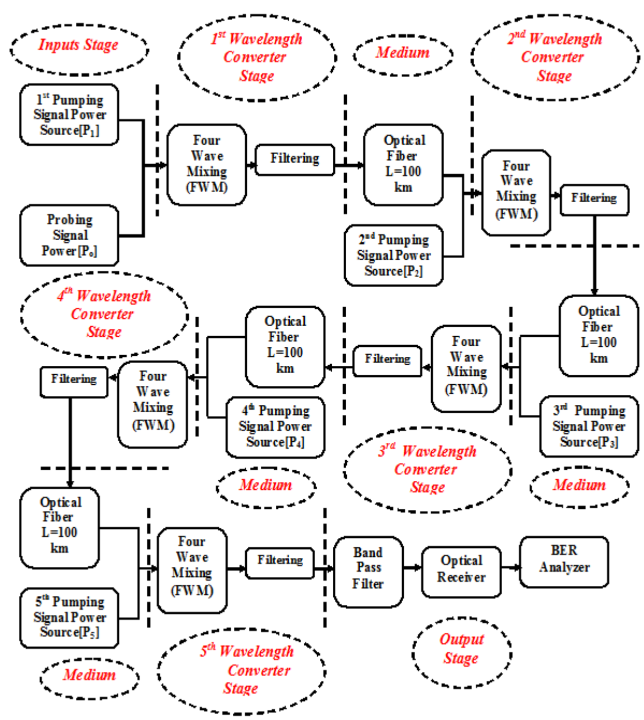

Fig. 2 General block diagram for the five-cascaded stages SOA-based wavelength converter

Probing and 1st Pumping signals are combined together at input stage. Then, two input signals (P_o and P_1) undergo processing in FWM module at the first conversion stage, producing two converted signals at two new wavelength channels carrying the same data (information) contents at the probe signal wavelength.

The selection of the preferable 1st converted signal is processed through filtering. Afterwards, the 1st converted signal passes through an optical fiber of length of 100 km and combined again with the other pumping signals (i.e. P_2, P_3, P_4 and P_5). Repeating the same steps processed at first wavelength conversion stage in order to achieve the second, third, fourth and fifth wavelength conversion process.

Finally, at output stage, the 5th converted wavelength will be carried at the same data of the probing signal extending the conversion range.

III. SIMULATION SETUP

Figure 3 shows the proposed setup which is used to realize only two stages cascaded wavelength converter operations, covering all-optical C-band. While, Fig. 4 represents an extension setup of other three cascaded stages covering another optical range, namely L-band. Table. I represents the overall components/parameters and their corresponding values which are used to simulate and evaluate the proposed wavelength converters and extracted from related literatures [4, 30].

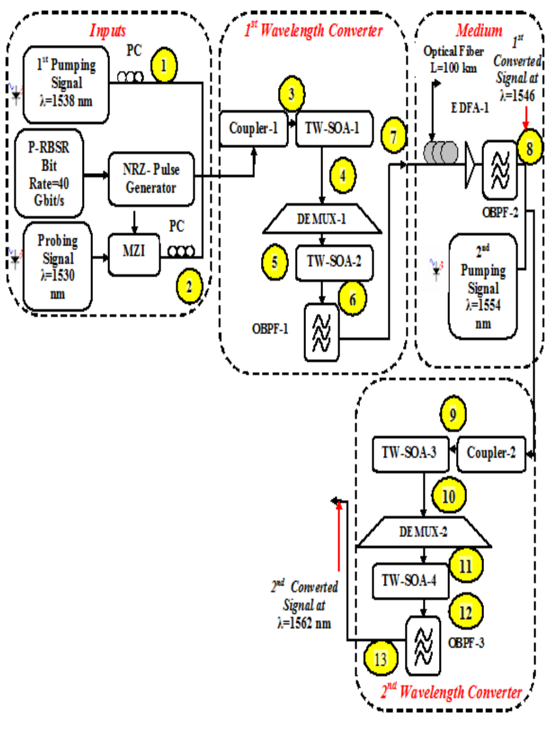

Fig. 3 Proposed setup for two-cascaded wavelength conversion spanning 100 km transmission in a single-mode fiber. PC: Polarization Controller, EDFA: Erbium-Doped Fiber Amplifier, OBPF: Optical Band-Pass Filter, MZI: MOD: LiNbO3 Mach-Zehnder Modulator, TW-SOA: Traveling Wave Semiconductor Optical Amplifier, P-RBSR: Pseudo-Random Bit Signal Generator, NRZ: Non-Return to Zero, DEMUX: Demultiplxer.

The probing signal source (P_0) and pumping signal sources (P_1 and P_2) are emitted utilizing continuous wave lasers. The probing signal (P_0) is simultaneously modulated by a 2^{10}-1 bit sequence using $LiNob_3$-Mach-Zehnder modulator with NRZ data format at 40 Gbit/s.

After modulation, 1st pumping signal (P_1) is combined with probing signal (P_0) at Point (3) as shown in Fig. 3 through 3-dB coupler-1 and mechanical polarization controllers which are used to independently align the pumping and probing signals to the TE polarization of the SOA.

Subsequently, the combining signal exposes to the FWM-1 medium, which consists of 0.5-mm long commercial traveling wave semiconductor optical amplifier (TW-SOA-1) operating at 250-mA bias current. At the output of the TW-SOA-1 (Point (4)), the 1st converted signal is isolated using WDM-DEMUX-1 at Point (5).

At Point (6), we obtain the 1st converted signal from the FWM-1. After demultiplexing, the 1st converted signal is amplified through TW-SOA-2 and filtered through OBPF-1.

In this experiment, dual sources provide the pumping waves for the two converters spanning 100-km transmission link between them, then in order to compensate the propagation losses in the 100 km length of dispersive single-mode fiber (SMF) at Point (8), EDFA-1 - OBPF-2 pair is employed. Afterwards, 2nd pumping signal (P_2) and 1st converted signal are coupled again at Point (9) through 3-dB coupler-2, then injected to FWM-2 module consisting of TW-SOA-3, DEMUX-2 and TW-SOA-4. It is observed that the second wavelength conversion is achieved by generating other converted signals depending on the nonlinearity mechanism of passing through TW-SOA-3 at Point (10), and then the 2nd converted signal is separated by DEMUX-2 at Point (11) and amplified through TW-SOA-4 at Point (12). Finally, the 2nd converted signal is taken after OBPF-3 at Point (13).

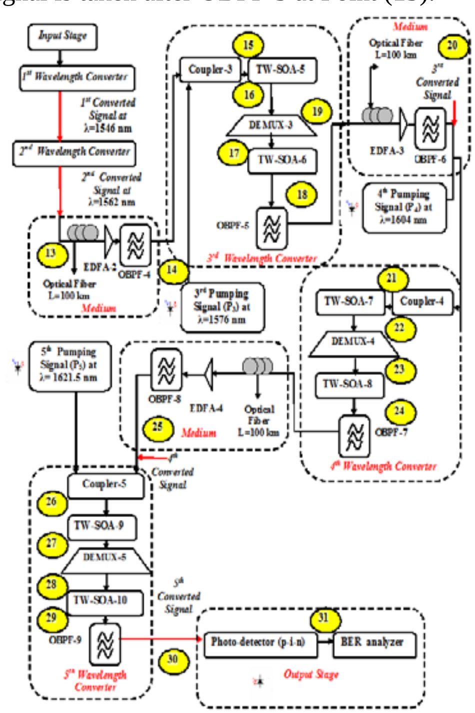

Fig. 4 Proposed setup for five-cascaded wavelength conversion spanning 400 km transmission

Figure 4 shows that, the 2nd converted signal and 3rd pumping signal (P_3) are merged together through 3-dB coupler-3 at Point (15) after passing through 100 km again in addition to EDFA-2 - OBPF-4 pair (Point (14)). Then, the 3rd converted signal is obtained at Point (18) after FWM-3 module consisting of TW-SOA-5, DEMUX-3 and TW-SOA-6 and filtered through OBPF-5 at Point (19).

Subsequently, in order to get the 4th and 5th converted signals, the same steps are repeated as mentioned at Fig. 3, according to the procedure, which is presented in Fig. 4 starting from Point (19) and ending at Point (30). Finally, in the receiver, the 5th converted signal is detected using photo-detector (p-i-n) at Point (31) and this receiver output is then introduced by a probe at the bit-error rate (BER) analyzer input in order to facilitate both Q-factor and BER measurements.

Table I. Components, parameters and values

Components	**Parameters**	**Value Range**	**Unit**
		Inputs	
CW Laser Source (Probing Signal)	Center Frequency	1530	[nm] [THz]
		195.943	
CW Laser Source (1st, 2nd, 3rd, 4th, 5th) Pumping Signals		1538-1621.5	
		194.9-184.9	
Pseudo-Random Bit Sequence Generator	Bit-Rate	40	Gbits/s
NRZ Pulse Generator	Rectangle Shape	Gaussian	N/A
LiNob3 MZM	Splitting Ratio	1.3	N/A
	Bias Voltage 1	+3	V
	Bias Voltage 2	-3	
		1st to 5th Wavelength Converters	
Polarization Controller	Phase	[90,-90[	deg
Pump Coupler Co-Propagating 3-dB couplers	Signal Attenuation	0	dB
	Pump Attenuation	0	
Traveling Wave Semiconductor Optical Amplifier (TW-SOAs)	Length	0.0005	m
	Width	3×10^{-6}	
	Height	8×10^{-6}	
	Optical Confinement Factor	0.15	N/A
	Differential Gain	2.78×10^{-20}	m^2
	Carrier density at transparency	1.4×10^{24}	m^{-3}
	Line width enhancement factor	5	N/A
	Recombination Coefficient (A)	143000000	s^{-1}
	Recombination Coefficient (B)	1.0×10^{-16}	m^3s^{-1}
	Recombination Coefficient (C)	3.0×10^{-41}	m^6s^{-1}
	Initial carrier density	3.0×10^{24}	m^{-3}
	Injection Current	250	mA
WDM-DEMUXs	No. of output	2	N/A
	Bandwidth	10	GHz
EDFAs	Gain Control	25	dB
	Noise Figure	10	dB
OBPF - 1 to 9	Bandwidth	1	nm
		Medium	
Optical Fibers	Length	100	Km
		Outputs	
Optical Receiver	Photo-detector	PIN	N/A
	Cut-off Frequency	5	GHz
	Center Frequency	184.48766646	THz

IV. RESULTS AND DISCUSSION

This section is divided into two sub-sections (i.e. section IV. A and section IV. B). In section IV. A, two quantitative measurements are tested to show the efficiency of the proposed scheme, namely bit-error rate (BER) and conversion efficiency based on a power optimization study (i.e. pumping and probing signals powers) for the designed cascaded wavelength converter at 40 Gbit/s. Section IV. B represents full simulation results that realize the wavelength conversion operation of the proposed scheme after applying recommendations extracted from the optimization study at 40 Gbit/s.

IV. A. SIMULATION SETUP

This section targets extracting the optimum values of probing and pumping powers (i.e. P_o, P_1, P_2, P_3, P_4 and P_5) that achieve this work's aim. That is, realizing the wavelength conversion operation of the proposed converters with unique BER and high conversion efficiency at an acceptable power levels and injection current level.

The optimization process maintains the injection current (I) at specific value of 250 mA extracted from famous literatures [11, 13, 31, 32]. Noticing that the value of probing signal power (P_0) ranged from -3 to -1 dBm (from 0.502 to 0.7943 mW), while values of the pumping signals power (P_1, P_2, P_3, P_4 and P_5) varied from 0 to 6 dBm (from 1 to 3.981 mW) [11, 13, 31, 32].

FWM conversion efficiency is defined as the converted signal power at the TW-SOA output divided by signal power at TW-SOA input.

Firstly, the effect of the pumping signals (i.e. P_1, P_2, P_3, P_4 and P_5) are investigated while maintaining the injection current (I) at 250 mA and the probing signal (P_0) of -2 dBm which is chosen from our trials that achieve best values of BER in addition to high conversion efficiency. The results obtained in Fig. 5, showing that with increasing of pumping signals powers, the BER decreases, while the converted signal power keeps increasing and wavelength conversion process occurred successfully with the required BER and conversion efficiency.

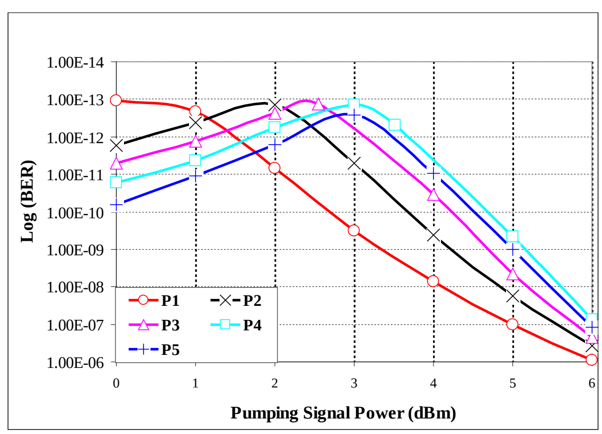

Fig. 5 Variation of pumping signals versus BER at P_0 = - 2 dBm and I = 250 mA

Its note worthy to observe that when the pumping signals power is higher than 5 dBm (3.162 mW), the converted signal power decreased due to the gain saturation effect of the TW-SOA, leading to have bad BER (i.e. higher than 10^{-10} for all pumping signals) for our proposed wavelength converter.

It is observed from Fig. 5, that the optimum values of pumping signals power (i.e. P_1, P_2, P_3, P_4 and P_5) achieving remarkable BER are 0, 2, 2.5, 3 and 3 respectively.

Again, after extracting the optimum values of the pumping powers, the procedure of calculating minimum BER and high conversion efficiency is repeated to study the effect of the probing signal (P_0), in the range of ($-3 \le P_0 \le -1$). Keeping the other affecting parameters constant (i.e. pumping signals and injection current), the obtained results are displayed in Figs. 6-7.

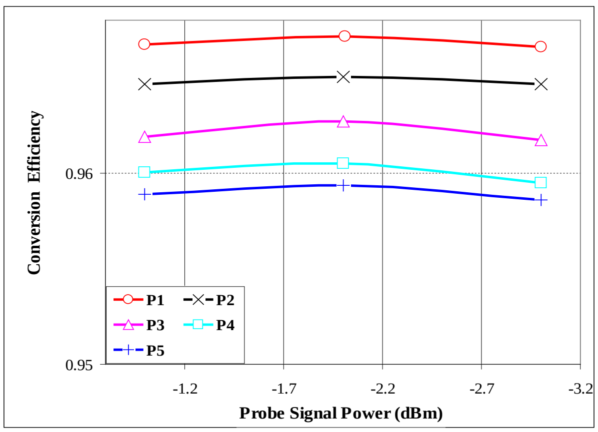

Fig. 6 Variation of probing signal (P_0) versus conversion efficiency at P_1=0, P_2=2, P_3=2.5, P_4=3 and P_5=3 dBm and I=250 mA

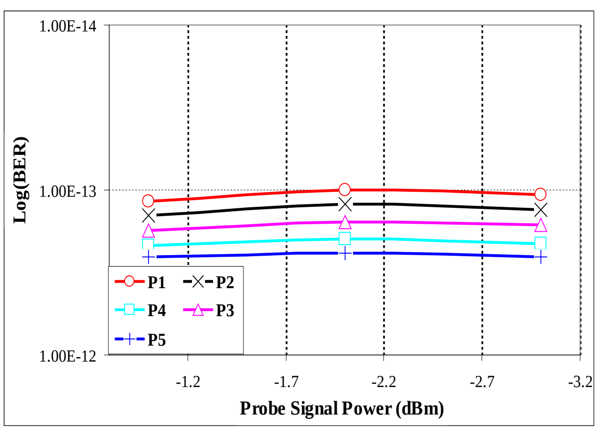

Fig. 7 Variation of probing signal (P_0) versus BER at P_1=0, P_2=2, P_3=2.5, P_4=3 and P_5=3 dBm and I=250 mA

It is clear from Figs. 6-7, that the probing signal (P_0) has a negligible effect on the values of the BER and conversion efficiency, assuring that the optimum value of (P_0) achieving remarkable BER in range of 10^{-13} and high conversion efficiency near 96% is about (-2 dBm).

IV. B. SIMULATION RESULTS

As described in details in section III, a complete system trace for the proposed wavelength converter depending on the optimized values that estimated in section (IV. A) is introduced in this section. As indicated, (Point (1)) represents the 1st pumping signal (P1) at λ=1538 nm with a power of 0 dBm as shown in Fig. 8.

While (Point (2)) provides the probing signal (P_0) at λ=1530 nm with a power of -2 dBm as seen in Fig. 9 but after modulation using $LiNob_3$-Mach-Zehnder modulator with NRZ data format at 40 Gbit/s.

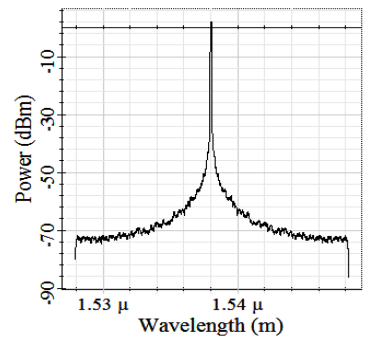

Fig. 8 1st pumping signal at λ=1538 nm

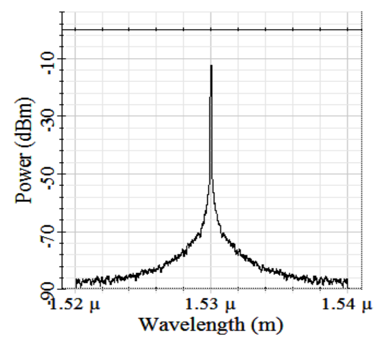

Fig. 9 Probing signal at λ=1530 nm

The 1st pumping signal (P1) and the probing signal (P_0) are merging together using 3-dB-coupler-1 at Point (3) as declared in Fig.10 and in order to transfer our data from the probing signal (P_0) located at wavelength 1530 nm to other converted signals at new wavelengths at Point (4), the merging signal must be introduced to TW-SOA-1 and the output is presented at Fig.11.

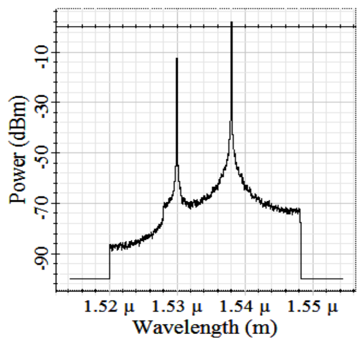

Fig. 10 1st pumping and probing signals combined together using a 3-dB coupler-1

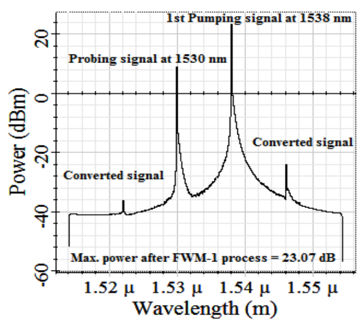

Fig. 11 Converted signals after exposing two signals (combining signals) to TW-SOA-1

Output results from passing the combining signal through TW-SOA-1, which is located at Point (4), showing two converted signals appear at wavelengths 1522 and 1546 nm respectively with maximum power of 23.07 dB. As up-conversion process is needed for achieving our proposed wavelength converter, so WDM-DEMUX-1 with bandwidth of 10 GHz will be used to filter the first converted signal at Point (5) which located at λ=1546 nm.

At Point (6), the 1st converted signal from the FWM-1 will be separated at λ=1546 nm after demultiplexing with maximum power equals 23 dB as appeared in Fig.12, which is comparable as obtained at Point (4) and that's executed by amplifying the signal at Point (5) using TW-SOA-2 with the same specification of TW-SOA-1.

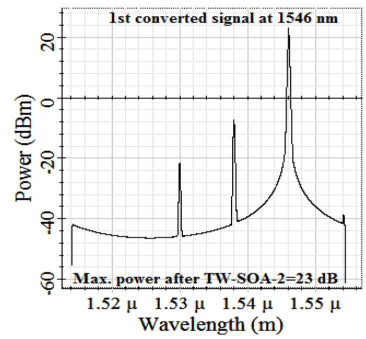

Fig. 12 1st converted signal after applying DEMUX-1 and TW-SOA-2

Then at Fig.13, the 1st converted signal at Point (7) will be isolated from its neighbor's signals by passing through OBPF-1, which specified by 1 nm bandwidth and center frequency of 193.915 THz with maximum power of 22.9 dB with conversion efficiency equals 99%.

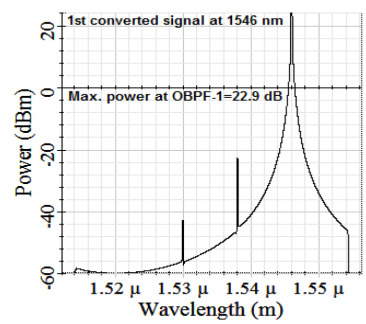

Fig. 13 1st converted signal after exposing to OBPF-1

Resulting from our first wavelength converter, the signal is up shifted in wavelength from λ=1530 nm as shown in Fig. 9 to λ=1546 nm which introduced at Fig. 13, so the first conversion range achieves 16 nm at Point (7) which is presented in Fig. 3 at section III.

Afterwards, the 1st converted signal propagates a distance of hundred kilometers through a dispersive single-mode fiber (SMF), leading to great propagation losses. These losses will be compensated using EDFA-1 with a gain of 25 dB, which is used to amplify the signal. Following the amplification, an optical band pass filter (OBPF-2) is used to reduce the amplified spontaneous emission (ASE) in order to provide improved OSNR of the 1st converted signal at Point (8). Maximum power of 1st converted signal after spanning 100 km and exposing to EDFA-1-OBPF-2 pair estimated of 21.8 dB and that's will be extracted from Fig.14.

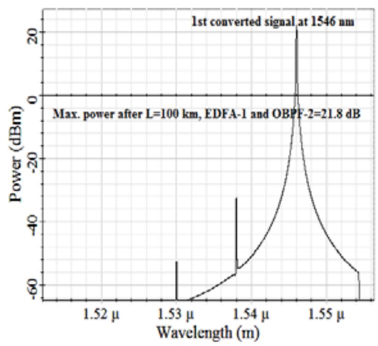

Fig. 14 1st converted signal after spanning 100 km, Then exposing to EDFA-1 and OBPF-2

Subsequently, the 2nd pumping signal (P_2) at λ=1554 nm with a power of 2 dBm is shown in Fig. 15. Then, 1st converted and 2nd pumping signals are combined again at Point (9) through 3-dB coupler-2. Then repeated the same steps as performed previously in order to achieve 2nd wavelength converter through injection of coupled signal (i.e. 1st converted and 2nd pumping signals) to FWM-2 module consisting of TW-SOA-3, DEMUX-2 and TW-SOA-4 during Points (9-12) as shown at Fig. 3 in section III.

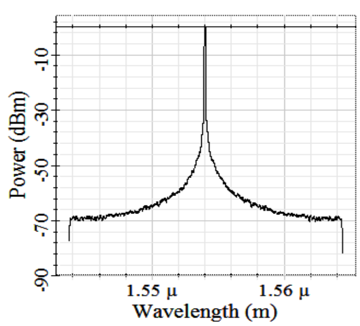

Fig. 15 2nd pumping signal at λ=1554 nm

So 2nd wavelength conversion process is displayed as seems at Figs. 16-17 with maximum power degraded from 21.2 to 20.96 dB.

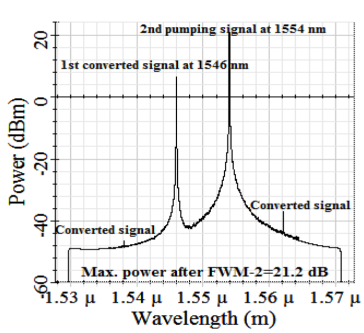

Fig. 16 2nd pumping and 1st converted signals coupled using 3-dB-coupler-2 and introduced to TW-SOA-3

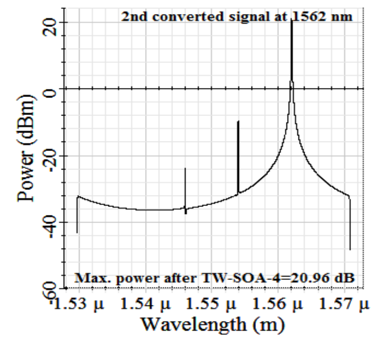

Fig. 17 2nd converted signal after applying DEMUX-2 and TW-SOA-4

The 2nd converted signal was isolated at Point (13) by passing through OBPF-3, which described by 1nm bandwidth and center frequency of 191.929 THz with maximum power equals 20.9 dB as shown in Fig.18.

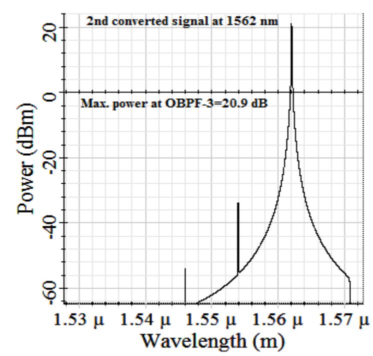

Fig. 18 2nd converted signal after Exposing to OBPF-3

In the second wavelength converter, the signal is up shifted again approximately by an equal amount that obtained in the first wavelength converter as it is ranging from λ=1546 to λ=1562 nm. Therefore as a result we can transfer our data from λ=1530 nm to λ=1562 nm at approximately 32 nm as a conversion range with conversion efficiency of 98.6%, using only two cascaded stages which cover approximately all-optical C-band ranging from (1530 nm to 1565nm) [33].

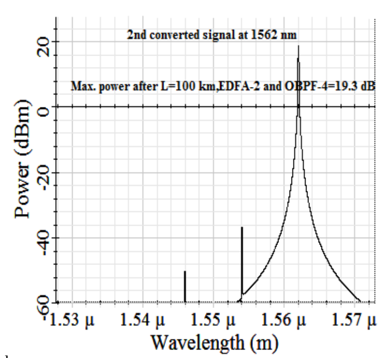

Fig. 19 2nd converted signal after spanning 100 km, then exposing to EDFA-2 and OBPF-4

After covering all-optical C-band, the 2nd converted signal at wavelength of 1562 nm propagates again distance of 100 km, amplified through EDFA-2 with a gain of 25 dB and filtered by OBPF-4 at Point (14) with maximum power equals 19.3 dB as shown in Fig. 19. Then, the 2nd converted signal coupled with 3rd pumping signal at Point (15) at wavelength of 1576 nm and introduced to TW-SOA-5 as displayed in Fig. 20. Subsequently, extracting of 3rd converted signal at Point (18) at wavelength of 1590 nm after applying DEMUX-3, TW-SOA-6 and OBPF-5 with maximum power of 17.631 dB is done as seen in Fig. 21, with conversion efficiency of 98.9 %.

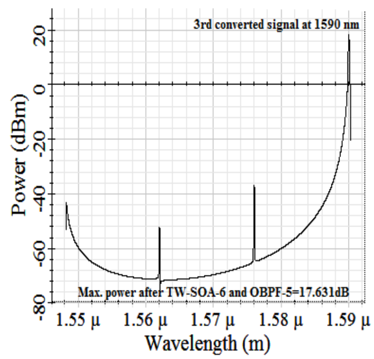

Fig. 20 3rd pumping and 2nd converted signals coupled using 3-dB-coupler-3 and introduced to TW-SOA-5

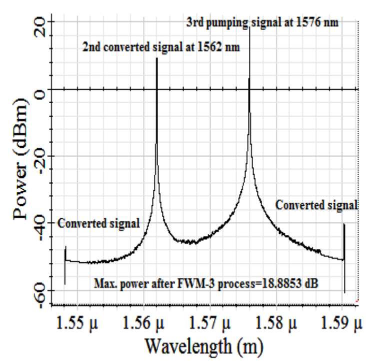

Fig. 21 3rd converted signal after applying DEMUX-3, TW-SOA-6 and OBPF-5

Repetition of 4th and 5th wavelength converter stages with the same procedure as shown in Fig. 4 from (Point (19)) to (Point (30)), having degradation of maximum power from 16.1 to 12.94 dB with power penalty near 3.16 dB. Figs. 22-27, showing the 4th, 5th converted signals at wavelengths of 1618 and 1625 nm respectively with conversion efficiency of 98.4% and 98.8% respectively, covering all-optical L-band which ranging from 1565 till 1625 nm.

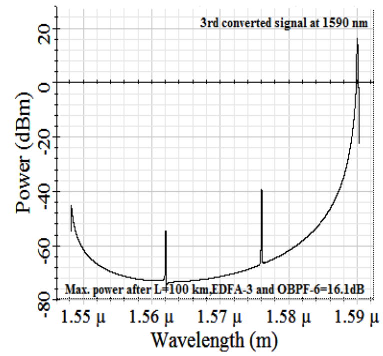

Fig. 22 3rd converted signal after spanning 100 Km, then exposing to EDFA-3 and OBPF-6

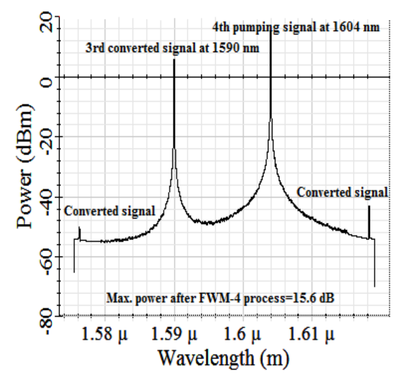

Fig. 23 4th pumping and 3rd converted signals coupled using 3-dB-coupler-4 and introduced to TW-SOA-7

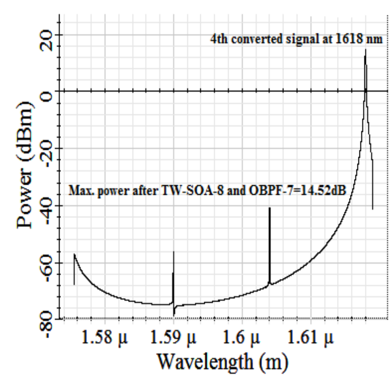

Fig. 24 4th converted signal after applying DEMUX-4, TW-SOA-8 and OBPF-7

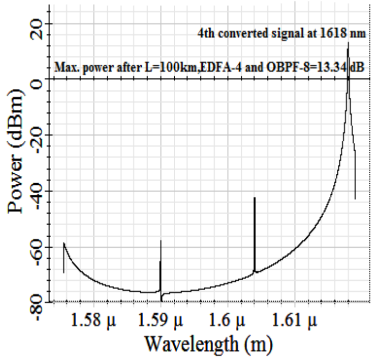

Fig. 25 4[th] converted signal after spanning 100Km, then exposing to EDFA-4 and OBPF-8

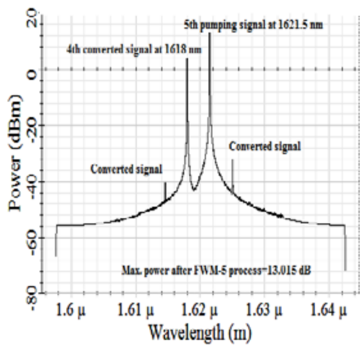

Fig. 26 5[th] pumping and 4[th] converted signals coupled using 3-dB-coupler-5 and introduced to TW-SOA-9

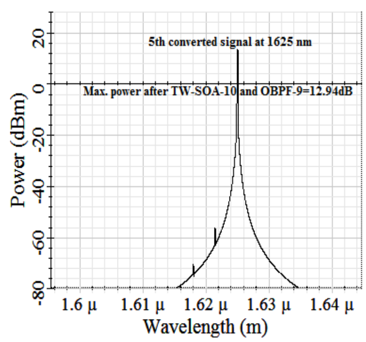

Fig. 27 5[th] Converted Signal After applying DEMUX-5, TW-SOA-10 and OBPF-9

Tables II and III summarize the optimum values of the affecting parameters (i.e. probing and pumping power signals) and its corresponding system outputs (i.e. conversion range and conversion efficiency) in order to realize the proposed multiple cascaded wavelength converters (i.e. five cascaded wavelength converters) which operating at 40 Gbit/s, covering C-L optical bands.

Table II. Optimum values of the affecting parameters and their corresponding converted wavelengths at 40 Gbit/s

Probing Signal Wavelength [nm]	Pumping Signal Wavelength [nm]	Injection Current [mA]	Converted Signal	Wave-length [nm]
1530 (P_s= -2 dBm)	1538 (P_1=0 dBm)	250	1st	1546
	1554 (P_2=2 dBm)		2nd	1562
	1576 (P_3=2.5 dBm)		3rd	1590
	1604 (P_4=3 dBm)		4th	1618
	1621.5 (P_5=3 dBm)		5th	1625

Table III. Converted wavelengths values and their corresponding conversion efficiency system outputs at 40 Gbit/s

Wave-length [nm]	Conv. Range [nm]	Optical Band	Converted Signal Power at TW-SOA Output [dB]	Converted Signal Power at TW-SOA Input [dB]	Conv Effi. (%)
1546	16	C-Band Ranging from [1530-1565]	23.07	23.3	99.0
1562	32		21.2	21.5	98.6
1590	60	L-Band Ranging from [1565-1625]	18.8853	19.09265	98.9
1618	88		15.6	15.85	98.4
1625	95		13.015	13.1775	98.8

Its note worthy, that this work's aim succeeded to cover the all C-L optical bands with approximated constant conversion efficiency near 98% as shown in Fig. 28 for the proposed five stags of cascaded wavelength converters.

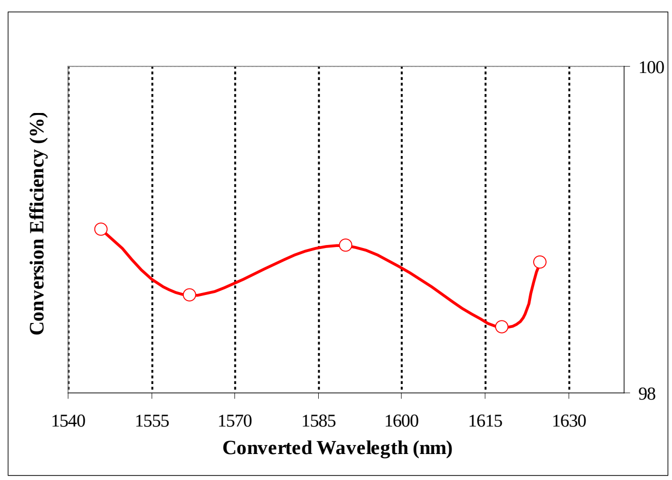

Fig. 28 Variation of the converted wavelengths signals versus conversion efficiency

Finally from Figs. 5-7, our proposed five stages cascaded wavelength converter with a unique BER near 10^{-13} and a remarkable conversion efficiency above 98% with an acceptable converter complexity are realized by hiring an optimized values of probing signal power (P_0) of -2 dBm, pumping signals power (i.e. P_1, P_2, P_3, P_4 and P_5) of 0, 2, 2.5, 3 and 3 dBm respectively, in addition to the most famous value of the injection current (I) of 250 mA. A comparison with related literatures that utilize the same technique and converter design is carried at Table. IV to prove the merits of this work. From this table, it can be shown that the proposed scheme outperforms works in [11, 27, 31, 32, 34], in sense of spanning distance, bit-rate and BER. In other hand, unfortunately it has high power penalty as compared to [11, 27, 31, 32, 34]. In addition, it gives comparable results in sense of conversion efficiency compared to [11]. Finally, the proposed scheme gives better results in sense of up-conversion range compared to [26, 27, 31, 32, 34].

Table IV. Comparison between the proposed work and its related works

Ref.	Dist. (Km)	Bit Rate (Gbit/s)	BER	Up Conv. Range (nm)	Conv Effi. (%)	Power Penalty (dB)
[34]	40	10	10^{-9}	9	NA	2.2
[31]	NA	10	10^{-10}	25	NA	2.5
[11]	80	10	10^{-4}	NA	Free-error 100%	4
[27]	20	10	10^{-12}	10	NA	2
[32]	NA	10	10^{-9}	35	NA	1
[26]	NA	40	NA	2	NA	NA
Proposed Work	400	40	10^{-13}	95	98	10.06

V. CONCLUSION

In this work, a new scheme of multiple cascaded wavelength converters using FWM technique is proposed. It is suggested to utilize two commercial TW-SOA for each wavelength converter stage rather than using only one SOA in addition to Erbium-doped fiber amplifiers (EDFAs) as in the conventional schemes. This proposal overcomes the main problem of OSNR degradation due to the effect of the amplified spontaneous emission, emitting by EDFAs. The main idea behind this proposed scheme, covering C-L optical bands with remarkable BER and high conversion efficiency.

A complete trace for the proposed five stages wavelength converters is carried out. Optimization process is taken into our consideration in this work. Based on the simulation results, bit-error-rate performance near 10^{-13} at 40 Gbit/s is achieved up to 95 nm as a conversion range. A power penalty of 10 dB with a remarkable conversion efficiency of 98% (i.e. approximately free-error) is measured for overall system, which gives better contribution overcoming one of the drawbacks of FWM technique that is having low conversion efficiency.

Finally, after making a comparison between the results of our main work and related literatures, it is clear that this work gives merits for the network designers to utilize commercial components in all-optical signal processing.

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