RESEARCH ARTICLE OPEN ACCESS

Performance comparison of four-wave mixing (FWM) in a single semiconductor optical amplifier (SOA) based all-optical up/down wavelength converter for advanced modulation formats (CSRZ, DBRZ and MDBRZ) on the basis of power penalties

Inderjeet kaur[1], Karamdeep Singh[2], Shivinder Devra[3], Gagandeep kaur[4]
[1,2,3]Department of Electronics Technology, Guru Nanak Dev University, Amritsar,
[4]Department of Electrical & Instrumentation Engineering, Thapar University, Patiala,

Abstract:

In this article, the bit error rate (BER) analysis of four-wave mixing (FWM) in semiconductor optical amplifier (SOA) based wavelength converter is carried out for various modulation formats such as carrier suppressed return to-zero (CSRZ), duo binary return to-zero (DBRZ) and modified duo binary return to-zero (MDBRZ). The performance analysis is performed at following bit rates: 10 Gbps, 20 Gbps and 40 Gbps. The power penalty of each format is determined. Lower the power penalty better is the performance. It has been noticed that CSRZ gives better performance at 10 Gbps while at 20 Gbps DBRZ performs better than the other and again at 40 Gbps line rates, CSRZ exhibits better performance as compared to two advanced modulation formats.

Keywords **— Wavelength conversion, Four Wave Mixing (FWM), Modulation Format, CSRZ, DBRZ, MDBRZ.**

1. Introduction

Wavelength Conversion is a method of enhancing network properties eg. Re-configurability, non-blocking capability and wavelength reuse [1]. Wavelength conversion techniques are needed in increasing the flexibility and efficiency of optical networks by using dynamic reallocation of optical channels. Furthermore Wavelength Conversion techniques have gained much attention as they can play a vital role in future WDM optical networks. Till the time, various methods have been proposed and demonstrated based on different type of propagation media and devices such as SOA, HNLF, PPLN, NOLM etc. [2, 3, 4].

The function of a Wavelength converter as suggested by its name is to convert an injected signal of light from one wavelength to a desired wavelength in a network. The SOA based wavelength converter usually exploit 3rd order nonlinearities which are mainly of four types: cross gain modulation (XGM), cross-phase modulation (XPM), self-phase modulation (SPM) and four wave mixing (FWM). Based on exploiting these nonlinearities, different wavelength conversion exhibit different advantages and disadvantages. For example, using XGM (XGM is a non-linear phenomena usually observed in SOA, in which gain of signal centered at one wavelength can be affected by signal at other wavelength due to carrier density changes taking place in SOA) [5], the advantage is simplistic configuration, high conversion efficiency and the high bit rate capabilities (up to 40Gbps), But it also suffers from many drawbacks such as requirement of large amount of input power to saturate SOA, high noise figure, inverted signal at the output in comparison to input signal etc [6].

As an alternate, the XPM method can be utilized to overcome disadvantage of XGM, by placing one or more SOA's in an interferometric type of configuration. Further these two (XGM, XPM) don't offer transparency to bit rate and modulation format. This disadvantage can be removed using the other nonlinearity i.e. FWM which has become one of the favorable methods of wavelength conversion, offering numerous benefits such as transparency to bit rate and modulation format and preserves both the phase and amplitude information [7].

Yu, J. et al. (2000) realized wavelength conversion technique which was based on an NOLM at 40 Gbps and they investigated the walk off effect when the NOLM was used as a wavelength converter [8].

Gurkan, D.et al.(2003) presented the demonstration of all-optical simultaneous label swapping and wavelength conversion of multiple independent wavelength-division multiplexed (WDM) channels with the use of periodically poled lithium niobate (PPLN) waveguides working as wavelength converters. Here the experimental results were presented with 2 WDM data channels at 10 Gbps for label swapping. Guard time of 400ps was introduced between payload and the label and power penalty observed was less than 3dB.It has been claimed that the method presented could potentially accommodate 10 WDM channels simultaneously over the 40nm – shifting bandwidth of PPLN waveguides in C-band [9].

Vegas Olmos, J. J. et al. (2005) reported the experimental demonstration of wavelength multicasting to three different channels of a signal simultaneously at a bit rate of 10 Gbps with the use of FWM (four wave mixing) in a highly nonlinear fiber (HNLF). The channel spacing was noted to be 200GHz in C-band and the power penalty was observed to be less than 2.5 dB. At that time multicasting capability was a new feature requested to the physical wavelength converter [10].

Jansen, S. L. et al. (2005) presented the demonstration of a compact integrated all-optical wavelength converter based on an asymmetric sagnac loop. It gave the idea of how a 40 Gbps non-return-to-zero data signal could be converted over the entire C-band employing an asymmetric Sagnac loop. A receiver sensitivity power penalty of near about 2.1 dB was measured for both down and up-conversion cases [11].

Zhang, J. et al. (2008) demonstrated flexible wavelength conversion practically. The scheme presented was based on cascaded $\chi^{(2)}$ process in a periodically poled MgO doped $LiNbO_3$ of 20 nm. In this scheme, the input signal wavelength could be directly converted to output wavelengths within second harmonic bandwidth (up to 25 nm) [12].

Wu, X. et al. (2009) realized the tunable optical wavelength conversion of 10 Gbps signal which was RF (radio frequency) tone assisted OFDM (orthogonal frequency-division-multiplexing) signal, by means of PPLN (periodically poled lithium niobate) waveguide. It provided approximated 5 dB conversion efficiency over approximated tuning range of 30nm in C-band. Subcarriers up to 360 and 16 QAM was demonstrated and for that the power penalty obtained was less than 3dB [13].

Stamatiadis, C. et al. (2011-12) presented an optical wavelength conversion of ultra-high speed using a hybrid integrated photonic circuit on a silicon-on-insulator substrate. The chip completed the performance for inverted and non-inverted wavelength conversions up to a bit rate of 160 Gbps along with power penalty of about 4.6dB [14].

Ahmad, H. et al. (2011) reported the demonstration of FWM (four wave mixing) generation system experimentally in a 100 m highly nonlinear fiber (HNLF). Ring configuration was used efficiently for the demonstration and it was the first of this kind. The conversion efficiency was measured to be approximate -4dB [15].

Ji, H. et al. (2012) demonstrated the wavelength conversion at 80 Gbps to two copies experimentally. This was done by taking out the red-shifted and blue-shifted sidebands from cross phase modulation (XPM) in a silicon nanowire simultaneously. Bit error rate for both the sidebands was measured to be 10^{-9} and the power penalty of approximate 2 dB was observed. The power penalty observed was just negligible (i.e. < 0.3dB at a bit error rate of 10^{-3}) [16].

It has been observed from the study of available literature that various wavelength converters have been demonstrated based on exploitation of various 2nd order and 3rd order non-linear effects utilizing a variety of mediums such as SOA, HNLF, PPLN etc. However, it has been observed that there is still scope of research in evaluation of FWM in single SOA based wavelength converter for various types of advanced modulation formats such as CSRZ, DBRZ and MDBRZ. So, in this article, we have evaluated the performance of a FWM in a single SOA based up/down wavelength converter for different advanced modulation formats such as CSRZ, DBRZ and MDBRZ in terms of power penalties.

This article is organized as follows: In section 1 a brief introduction is provided about the wavelength conversion and the studies that have reported so far related to field of wavelength converters. Then next in section 2, the non-linearity that has been exploited for implementation i.e. for wave mixing (FWM) has been described briefly. In section 3, the wavelength conversion and its types have been discussed. In section 4, the simulation setups of wavelength conversion have been discussed for various modulation formats. In section 5, Results and discussion have been elaborated. Conclusions have been addressed in section 6.

2. 2. Four Wave Mixing

The terms linear and nonlinear in optics mean intensity independent and intensity-dependent phenomenon respectively. Nonlinear effects in optical fibers happen due to change in the refractive index of the medium with optical intensity and inelastic scattering phenomena [17]. FWM (four wave mixing) is one among them and is a third (χ^3) type of non-linearity, which involves wave mixing process i.e. in this, three signals are injected in a non-linear medium and they get mixed under phase matching condition. As a result of their interaction, a forth signal is obtained at the receiver side. There are mainly two types of FWMs: Degenerate and Non-degenerate. In a degenerate FWM, two signals i.e. pump signal at a particular wavelength (ω_{pump}) and a data signal (ω_{signal}) are sent to a 3rd order non-linear device which can be either HNLF (highly non-linear fiber) or SOA (Semiconductor Optical amplifier) etc. If phase matching conditions are satisfied, then a new signal is generated whose wavelength is determined by the energy conservation rule [18]. i.e.

$$\omega_{converted1} = 2\,\omega_{pump} - \omega_{signal} \quad (1)$$

It can be said that the converted signal is a copy if its original signal. The only difference is that it is phase conjugated and its wavelength is converted from that of the original signal. The degenerate FWM signal does not keep the phase of original signal and not even the intensity shape [19].

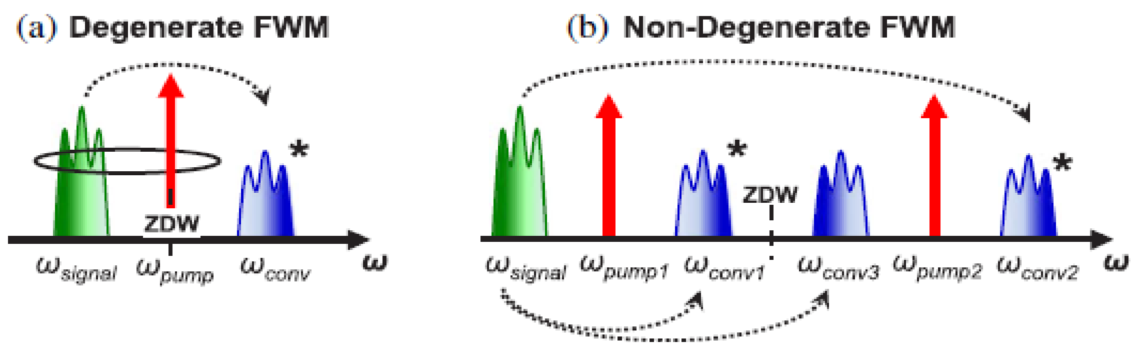

Fig. 1 De-generate and non-degenerate FWM [18]

Non-degenerate FWM is the case where two pump signals are taken as shown in Fig. 1 (whereas in case of degenerate FWM only one pump signal was there). The two pump signals having wavelength ω_{pump1} and ω_{pump2} are sent to non-linear device along with the data signal of wavelength $\omega_{signal,}$ and hence when the phase matching conditions are met then as a result of their interactions the mixing products (converted signals) are obtained i.e. [18]

$$\omega_{converted1} = 2\omega_{pump1} - \omega_{signal} \quad (2)$$

$$\omega_{converted2} = \omega_{pump1} + \omega_{pump2} - \omega_{signal} \quad (3)$$

$$\omega_{converted3} = \omega_{signal} + \omega_{pump2} - \omega_{pump1} \quad (4)$$

Here, simultaneous interactions occur in both pump signals, so both phase conjugating and non-phase conjugating wavelength conversion takes place in case of non-degenerate FWM [18].

3. Wavelength conversion

As described above, wavelength conversion is a technique which is used to put the data of one particular signal wavelength over another wavelength so as to enhance the efficiency of optical networks. If a signal can be converted to a desired wavelength in a transmission bandwidth, it can be used to perform many tasks eg. ADM (add drop multiplexing). Further, if coherent non-linear process could be used for wavelength conversion process, phase conjugated optical wave could be obtained and hence it could be used for the compensation of chromatic dispersion and for efficient high bit rate communication [20]. There are various wavelength conversion techniques. They are categorized mainly in three types:

1. OE-EO type in which optical signal is first converted to an electrical signal i.e. received by a photo-detector and then it is amplified reshaped and retimed to put it on different wavelength [20].
2. The second type is optical gating wavelength convertor which includes cross gain modulation (XGM) or cross phase modulation (XPM) nonlinearity's. Here modulation occurs at lasing wavelength. XGM provides the inverted waveform at the output after wavelength conversion. Further, in this type NOLM configuration can also be used, it uses non-linearity of optical fiber [21].
3. The third type of technique is coherent mixing of wave signals to generate a third wavelength eg. FWM and difference frequency generation (DFG) [20]. Comparing the latter two techniques, FWM is simpler because phase matching requirement is not that severe in this as compared to DFG.

4. System Setup

A generalized simulation setup utilized for the power penalty measurement of FWM in a single SOA based wavelength converter is shown in Fig. 2 as follows:

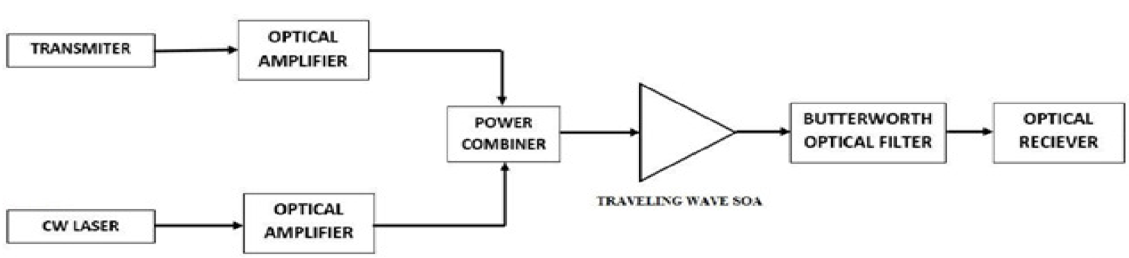

Fig. 2 Generalized simulation setup for wavelength converter based on FWM exploitation in SOAs

Fig. 2 represents wavelength converter based on FWM exploitation in SOAs. The transmitter includes one inetensity modulated pump signal cneterd at 1548 nm which has one of suitable modulation format (CSRZ or DBRZ or MDBRZ) and is kept constant for a particuler observation. The other arm has CW laser centerd at 1525 nm which serves as probe signal. The optical amplifiers deployed in each branch amplify bith pump and probe signals and then both signals are further fed to power combiner (PC). PC combines the two signals and further injectes both signals into SOA. The SOA parmeters used in the presen study are elucidated in Table 1 as follows:

Table 1. SOA physical parameter values

SOA Physical parameter	***Value***
Injection current (*I*)	600 mA
Amplifier length (*L*)	300 µm
Active region width (*w*)	1 µm
Active region thickness (*t*)	0.1 µm
Optical confinement factor (*Γ*)	0.4
Differential gain (A_g)	2.78×10^{-20} m^2
Transparency carrier density (N_0)	1.4×10^{24} m^3
Linear recombination coefficient (A_{nr})	1.43×10^{8} s^{-1}
Bimolecular recombination coefficient (B_{sp})	1×10^{-16} m^3 s^{-1}
Auger recombination coefficient (C_a)	3×10^{-41} m^6 s^{-1}
Initial carrier density (*N*)	3×10^{24} m^{-3}

Due to injection of pump and probe signals at appropriate wavelengths inside above said SOA, FWM process takes place which gives rise to new FWM idlers at frequencies $\omega_{converted1}$ = 1571 nm and $\omega_{converted2}$ = 1502 nm. These CW wavelengths are then further filtered with the help of Butterworth optical filter and are then fed to optical receiver section comprising of PIN diode, low-pass filter and a BER analyzer.

Further, as elucidated before, three types of transmitters having respective modulation formats have been considered in the presnet study. Fig. 3, 4, 5 show transmitter for DBRZ, MDBRZ & CSRZ modulation formats, respectively.They all make use of various components like continuous wave laser, mach-zehnder modulator (MZM) , RZ or NRZ pulse generator etc.

Firstly, the Duo binary modulation is a format for sending R bits/sec exploiting less than R/2 Hz of bandwidth. Duo binary signaling, also known as correlative coding, was initially developed in the period of electronic communications as a proficient way for reaching the Nyquist limit [23]. DBRZ transmitter comprises of different sub-blocks PRBS i.e. pseudo random binary sequence is the very first block of transmitter which is used to generate PRBS sequence (difficult to predict and exhibits statistical behavior) and its output is sent to not gate. After being inverted from not gate, the output goes to Duo pre-coder, Duo pre-coder is basically a technique which uses transmit diversity by weighing the information stream. It processes the signal and sends it to at two output unit i.e. NRZ generator which generates the non-return to zero pulse train and duo binary pulse generator. From here, output branch proceeds to MZM i.e. one output directly goes and the other one encounter electric gain of -1 unit. At MZM, a third input i.e. the pump signal wavelength also gets included whose data has to be put on a different wavelength for wavelength conversion purpose. The second block of mach zender modulator receives one direct sine wave signal and one sine wave signal with gain of -1 and after being processed, the output proceeds towards the SOA block. Duo binary Modulation is an effective method in high speed optical transmission systems to improve spectral efficiency [23].

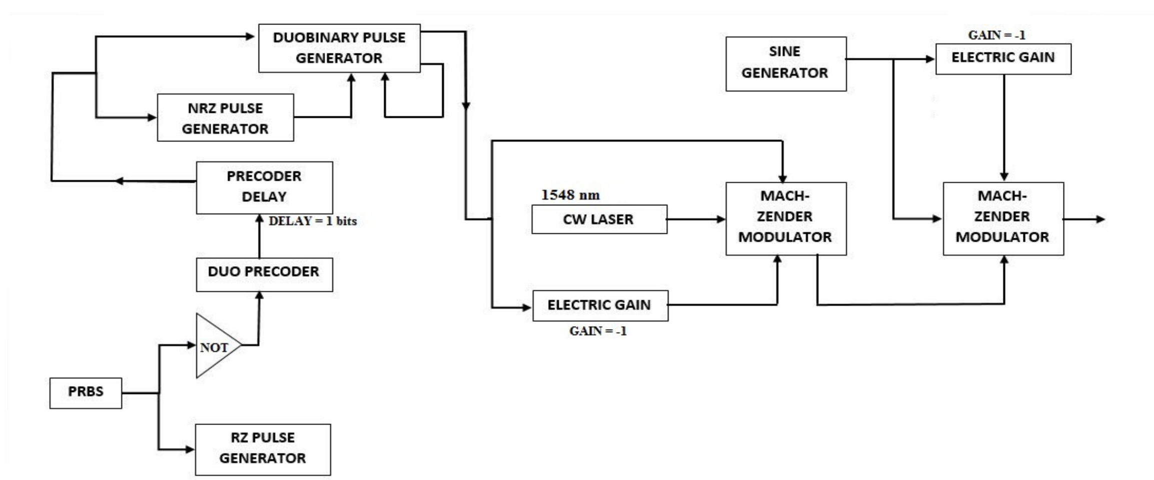

Fig. 3 Transmitter circuitary for DBRZ format

In MDBRZ transmitter, Pseudo random binary sequence (PRBS) generators having the ability to generate 2^7-1 long sequences are used to produce binary data streams [24] and it has two outputs, one is return to zero coder and the other one is duo pre-coder which weighs the input signal for security purpose and further a NRZ coder converts the signal to non return to zero format and give two outputs which gets combined i.e. one directly goes to combiner and the second one after encountering electric delay. From the combiner, again two output branches rise and reaches the mach zender modulator (one output directly and other through electric gain) where a third input from continuous wave laser is added and the merged product walks off to next mach zender block where two inputs from sine generator (working at 20 GHz) are inserted and the further output is processed by SOA [24].

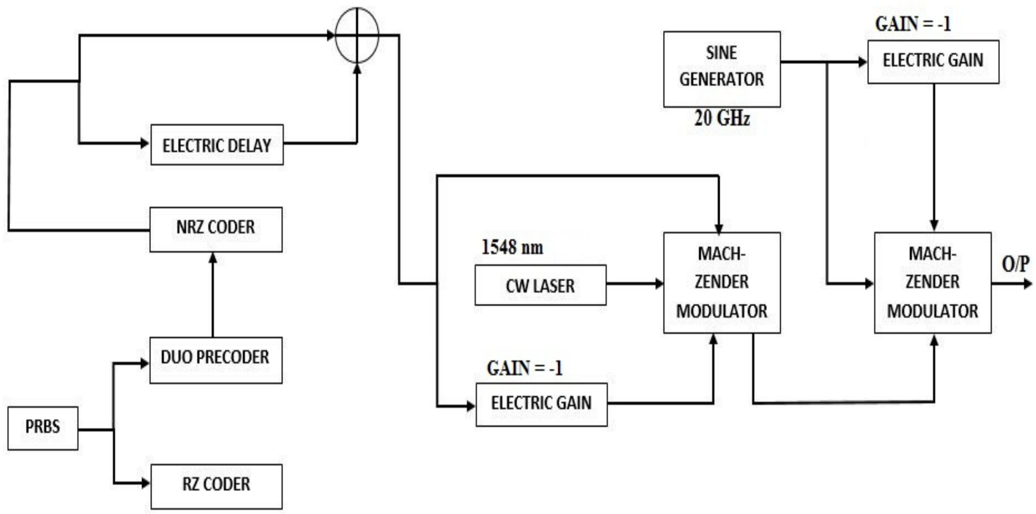

Fig. 4 Transmitter circuitry for MDBRZ format

In CSRZ transmitter, the initial block i.e. PRBS generates pseudo random bit sequence which upon going to NRZ block get converted to a non return to zero sequence and the two outputs from here meets at mach zehnder modulator one is directly proceeded to that and the other one encounter electric gain. At MZM another input called 'pump wave signal' generated by continuous wave laser is added and the combined output is received by second mach-zehnder modulator, this modulator receives two more inputs from sine generator (one straight and one again encountering electric gain) this merged output is processed by the further blocks of wavelength converter to provide suitable output.

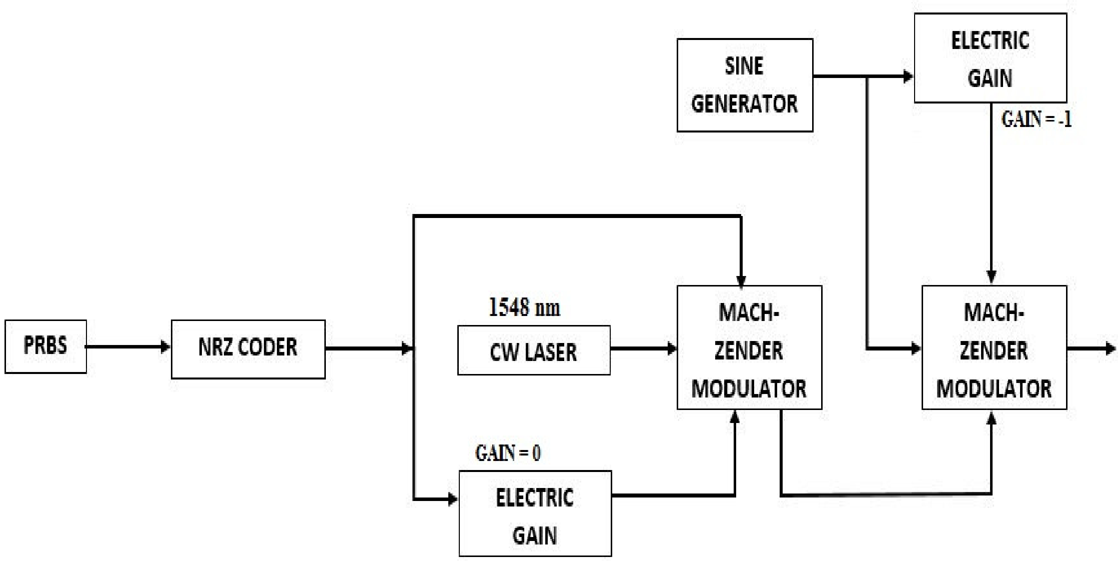

Fig.5 Transmitter circuitry for CSRZ format

4. Result and discussion

The BER calculations have been conducted for back-to-back signals for each modulation format (DBRZ, MDBRZ & CSRZ). Further, BER estimations of both up/down converted signals obtained by utilizing FWM in a single SOA converter, have been done for each modulation format (DBRZ, MDBRZ & CSRZ). This whole procedure is repeated at 10, 20 and 40 Gbps line rates. The power penalties in each case have been calculated at log (BER) = -9 level. The BER results obtained at 10 Gbps line rates are presented in Fig. 6 as follows:

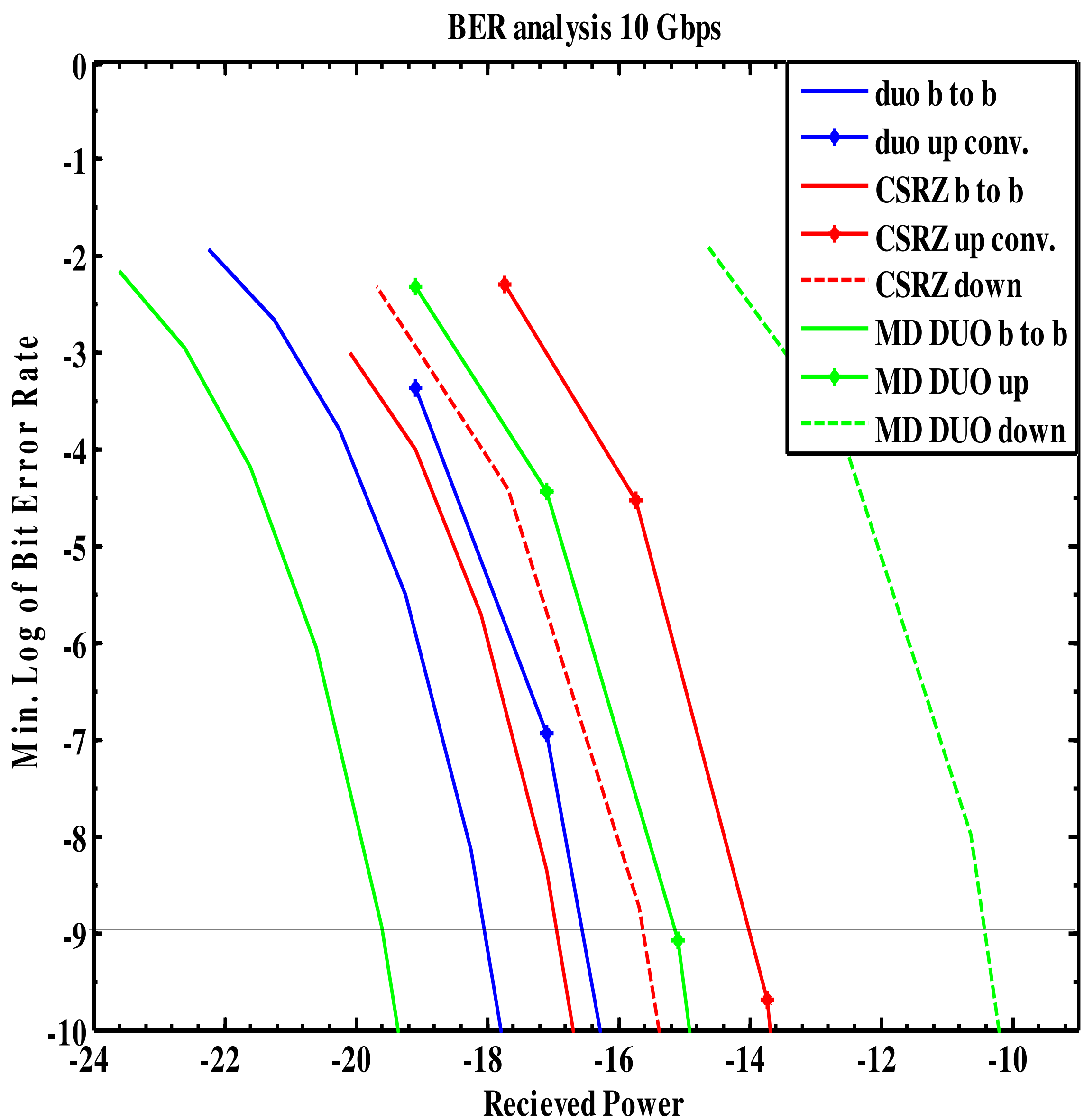

Fig. 6. Bit error rate analysis at 10 Gbps

At 10 Gbps, as shown in Fig. 6, the power penalty is observed to be approximately, 1.5 dB for DBRZ, 4.4dB for MDBRZ up converted signal, 9.2 dB for MDBRZ down converted signal and 1.3 dB for CSRZ down converted and approximated 6 dB for CSRZ up converted signal. Further, The BER results obtained at 20 Gbps line rates are presented in Fig. 7 as follows:

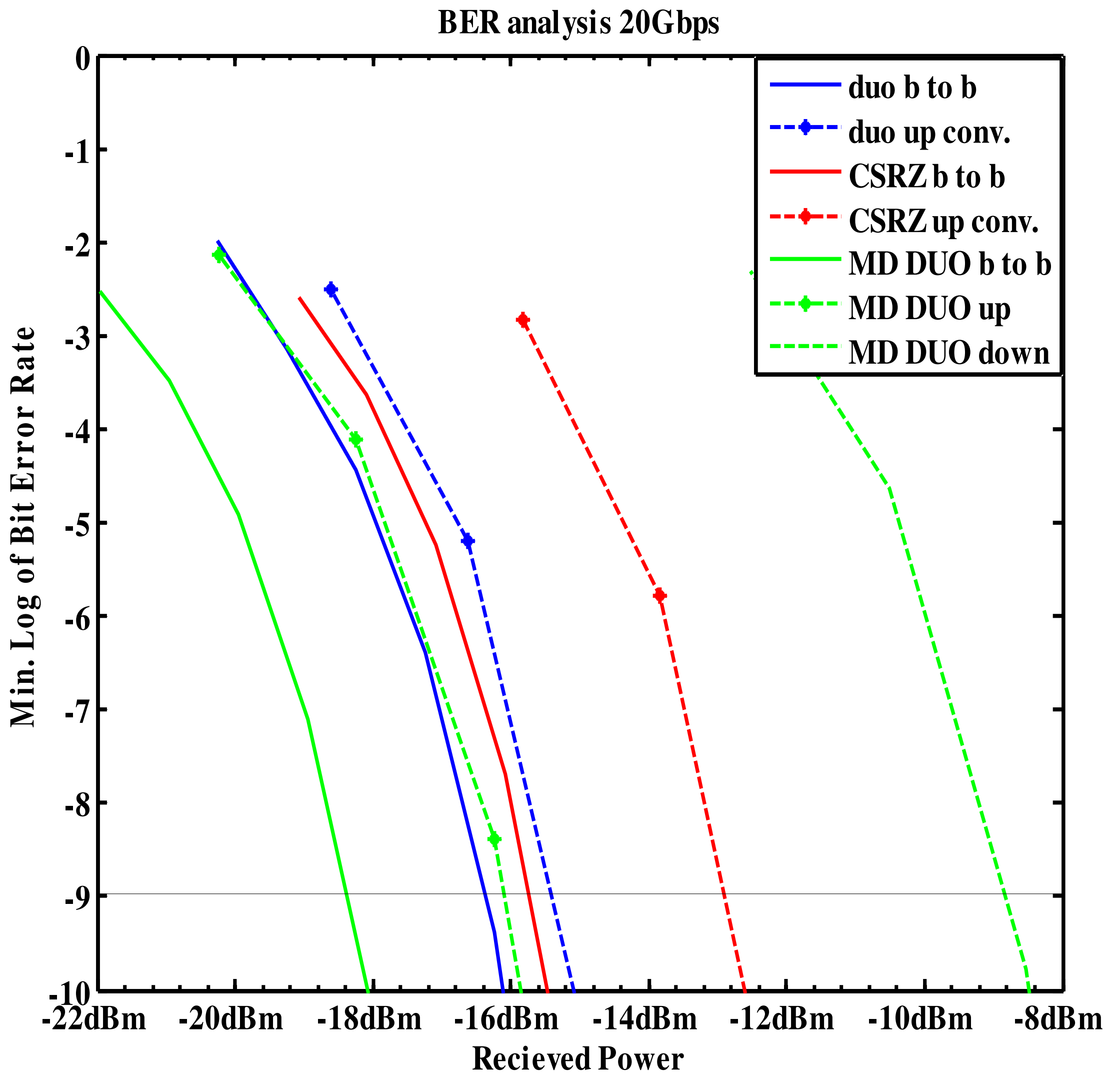

Fig. 7 Bit error rate analysis at 20 Gbps

At bit rate of 20 Gbps, as depicted in Fig. 7, power penalties are observed to be approximately 2.2 dB for up conversion and 9.6 dB for down conversion for MDBRZ format and it reaches to a value 1.1 dB for duo binary up converted signal. CSRZ up conversion has a power penalty of 2.7 dB. It can be noticed from BER calculations at 20 Gbps that DBRZ gives the best performance at 20 Gbps line rates. Additionally, the BER results obtained at 40 Gbps line rates are presented in Fig. 8 as follows:

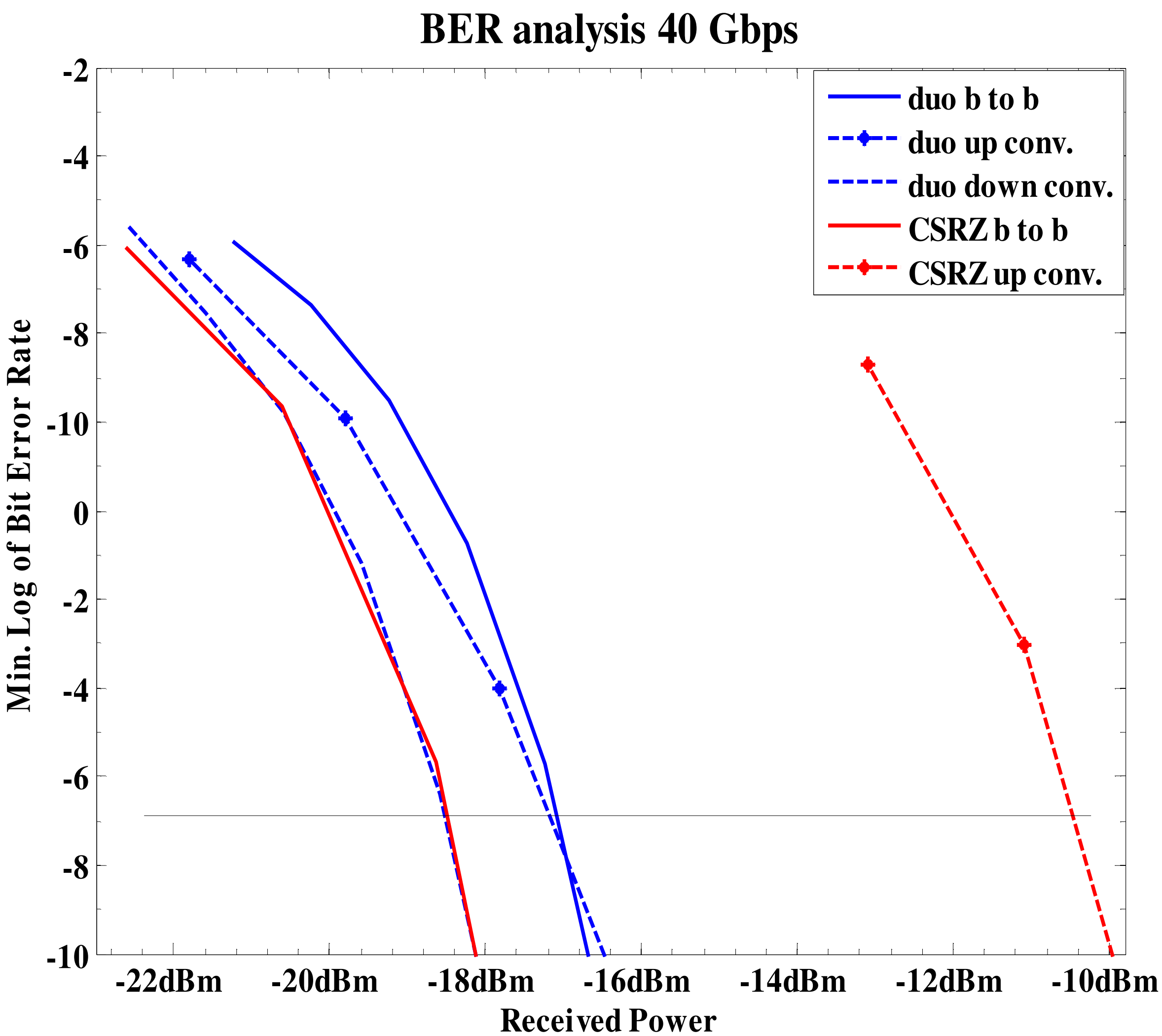

Fig. 8 Bit error rate analysis at 40Gbps

Here, when the observations are taken at 40 Gbps as shown in Fig. 8, it can be observed that CSRZ provides a receiver power penalty of approximate 8 dB for up conversion and has a zero-bit error rate for down conversion case which is not considered**.**

5. Conclusions

Bit error rate (BER) analysis has been carried out for a wavelength converter which is based on FWM harnessing in a single semiconductor optical amplifier (SOA). The BER analysis has been carried out at at following line rates: 10 Gbps, 20 Gbps and 40 Gbps for various advanced modulation formats such as CSRZ, DBRZ and MDBRZ. Corresponding power penalties for each modulation format (CSRZ, DBRZ and MDBRZ) for up/down converted wavelengths are measured and compared. It has been observed on the basis of power penalties obtained for all the three modulation formats that at 10 Gbps line rates CSRZ is the most suitable modulation format as it exhibits lowest power penalty. Whereas, at 20 Gbps and 40 Gbps DBRZ up converted signal & CSRZ signals, respectively are most suitable modulation formats.

REFERENCES

[1] Jourdan, A., Masetti, F., Garnot, M., Soulage, G., & Sotom, M. (1996). Design and implementation of a fully reconfigurable all-optical crossconnect for high capacity multiwavelength transport networks. Journal of Lightwave Technology, 14(6), 1198-1206.

[2] Singh, K., & Kaur, G. (2015). Interferometric architectures based all-optical logic design methods and their implementations. Optics & Laser Technology, 69, 122-132.

[3] Fu, S., Dong, J., Shum, P., Zhang, L., Zhang, X., & Huang, D. (2006). Experimental demonstration of both inverted and non-inverted wavelength conversion based on transient cross phase modulation of SOA. Optics Express, 14(17), 7587-7593.

[4] Cao, S. C., & Cartledge, J. C. (2002). Characterization of the chirp and intensity modulation properties of an SOA-MZI wavelength converter. Journal of lightwave technology, 20(4), 689.

[5] Singh, K., Kaur, G., & Singh, M. L. (2015). A single As 2 Se 3 chalcogenide Highly Non-Linear Fiber (HNLF) based

simultaneous all-optical half-adder and half-subtracter. Optical Fiber Technology, 24, 56-63.

[6] Farah Diana Mahad,Abu Sahmah M.Supa'at. "Comparative performance testing of SOA wavelength conversion techniques for future all-optical systems," International Journal for Light and Electron Optics (Optik), April 2012.

[7] Singh, S. (2008). Boost up of four wave mixing signal in semiconductor optical amplifier for 40Gb/s optical frequency conversion. Optics Communications, 281(9), 2618-2626.

[8] Yu, J., Zheng, X., Peucheret, C., Clausen, A. T., Poulsen, H. N., & Jeppesen, P. (2000). 40-Gb/s all-optical wavelength conversion based on a nonlinear optical loop mirror. Journal of lightwave technology, 18(7), 1001.

[9] Gurkan, D., Kumar, S., Willner, A. E., Parameswaran, K. R., & Fejer, M. M. (2003). Simultaneous label swapping and wavelength conversion of multiple independent WDM channels in an all-optical MPLS network using PPLN waveguides as wavelength converters. Journal of lightwave technology, 21(11), 2739.

[10] Vegas Olmos, J. J., Verdurmen, E. J. M., Tafur Monroy, I., Turkiewicz, J. P., de Waardt, H., Yan, N., & Koonen, A. M. J. (2005). Wavelength conversion with multicasting capabilities deploying highly nonlinear fiber for time-serial labeled networks.

[11] Jansen, S. L., Chayet, H., Granot, E., Ezra, S. B., den van Borne, D., Krummrich, P. M., ... & De Waardt, H. (2005). Wavelength conversion of a 40-Gb/s NRZ signal across the entire C-band by an asymmetric Sagnac loop. IEEE Photonics Technology Letters, 17(10), 2137-2139.

[12] Zhang, J., Chen, Y., Lu, F., & Chen, X. (2008). Flexible wavelength conversion via cascaded second order nonlinearity using broadband SHG in MgO-doped PPLN. Optics express, 16(10), 6957-6962.

[13] Wu, X., Peng, W. R., Arbab, V., Wang, J., & Willner, A. (2009). Tunable optical wavelength conversion of OFDM signal using a periodically-poled lithium niobate waveguide. Optics express, 17(11), 9177-9182.

[14] Stamatiadis, C., Stampoulidis, L., Kalavrouziotis, D., Lazarou, I., Vyrsokinos, K., Zimmermann, L., & Avramopoulos, H. (2012). Fabrication and experimental demonstration of the first 160 Gb/s hybrid silicon-on-insulator integrated all-optical wavelength converter. Optics express, 20(4), 3825-3831.

[15] Ahmad, H., Awang, N. A., Latif, A. A., Zulkifli, M. Z., Ghani, Z. A., & Harun, S. W. (2011). Wavelength conversion based on four-wave mixing in a highly nonlinear fiber in ring configuration. Laser Physics Letters, 8(10), 742-746.

[16] Lu, G. W., Sakamoto, T., & Kawanishi, T. (2014). Wavelength conversion of optical 64QAM through FWM in HNLF and its performance optimization by constellation monitoring. Optics express, 22(1), 15-22.

[17] Singh, S. P., & Singh, N. (2007). Nonlinear effects in optical fibers: Origin, management and applications. Progress In Electromagnetics Research, 73, 249-275.

[18] G. Agrawal, Nonlinear Fiber Optics. New York, NY, USA: Academic, 2001

[19] Agrawal, G. P. (2012). Fiber-optic communication systems (Vol. 222). John Wiley & Sons.

[20] Kaur, A. et al. ," Wavelength Converters in Optical Communication Systems", 3.2, (2013).

[21] Alan E. Willner et al.,"All-Optical Signal Processing", JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 32, NO. 4, FEBRUARY 15, 2014

[22] Kuwatsuka, V. I. V. W. V. (1999). Wavelength conversion technologies for photonic network systems. Fujitsu Sci. Tech. J, 35(1), 126-138.

[23] Kaur, R., & Dewra, S. (2014). Duobinary modulation format for optical system-a review. Int. J. Adv. Res. Electr. Electron. Instrum. Eng., 3, 11039.

[24] Singh, K., Kaur, G., & Singh, M. L. (2015). A single As 2 Se 3 chalcogenide Highly Non-Linear Fiber (HNLF) based simultaneous all-optical half-adder and half-subtracter. Optical Fiber Technology, 24, 56-63.