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Analyses of semiconductor optical amplifier (SOA) four-wave mixing (FWM) for future all-optical wavelength conversion

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ABSTRACT

Four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is currently one of the most attractive and promising wavelength conversion techniques for the all-optical future, and offers numerous advantages to the system designer. This paper investigates the performance of a 2.5 Gb/s SOA-based FWM wavelength converter system, in terms of its shifted wavelength conversion efficiency and optical signal-to-noise ratio (OSNR), for both up and down conversions. The converter is modeled and simulated using OptSim software, by varying the probe signal wavelength and power. It was found that the conversion efficiency and OSNR of the converted signal both decreased at large detuning wavelengths. Similarly, higher total SOA input powers worsened the conversion efficiency, but steadily improved the OSNR.

1. Introduction

The capacity of wavelength division multiplexing (WDM) is usually limited by several factors, such as the number of channels which can be deployed, wavelength congestion level and system management. A wavelength converter can be used to overcome such network limitations. A wavelength converter is an optical device which is used for the purpose of converting an injected signal of light from one wavelength to the desired wavelength in a system or network. Recently, the four-wave mixing (FWM) technique occurring within a semiconductor optical amplifier (SOA) has been one of the most favorable methods of wavelength conversion, offering numerous benefits to the system designer.

Unlike cross-gain modulation (XGM) and cross-phase modulation (XPM) wavelength converters, FWM offers transparency to the bit rate and modulation format, and hence preserves both the phase and amplitude information. Also, together with a proven large bandwidth of conversion (>100 nm), FWM is the only method with transparent optical properties, due to the unchanging nature of the optical properties of the information signal during the conversion process occurring within the SOA [1]. Additionally, SOA-based FWM wavelength conversion offers many other attractions; for example high bit rate capability – up to 10 Gb/s [2] or even 20 Gb/s [3] have been demonstrated. FWM methods are also capable of operating at high data rates without compromising the extinction ratio.

Off-setting these advantages, however, are various factors, such as the polarization sensitivity (which requires the polarization states of pump and probe to be matched, but normally <1 db) of the FWM process and the associated efficiency degradation at high detuning values, as well as the optical signal-to-noise ratio (OSNR) degradation due to the amplifies spontaneous emission (ASE) noise in the SOA. Since FWM is limited by its low conversion efficiency, it is therefore a crucial problem to retain a large SNR for the converted signal in cascaded wavelength converters.

The FWM mechanism in a SOA normally consists of two input optical waves, each having the same state of polarization, coupled into a saturated SOA, as shown in Fig. 1. Inside the active region of the SOA, the beatings of the two co-propagating waves modulate the carrier density, and therefore generate dynamic gain and index gratings. This nonlinear interference produces new waves, whereby these new waves do not overlap with other wavelengths. The intensity of the newly generated waves known as the $E_{\text{converted\_signal}}$ and $E_{\text{satellite\_signal}}$ is proportional to the product of the interacting wave intensities. E_{probe} is up-converted to a longer wavelength, $E_{\text{converted\_signal}}$ at an optical frequency of $\omega_{\text{CS}} = \omega_{\text{pump}} + \Delta\omega$, whereby $\Delta\omega$ refers to the detuning frequency. $E_{\text{converted\_signal}}$ is the phase conjugate replica of the original input signal.

Two crucial figures of merit which need to be considered for practical, high-quality wavelength converters are the conversion efficiency (dB) and the OSNR (dB) of the converted signal. The conversion efficiency (η) of any wavelength converter is defined as the ratio of the output converted signal power (P_{out}) with respect to input pump power (P_{in}), as shown in Eq. (1) [4]. The efficiency of the wavelength converter decreases with larger detuning frequency,

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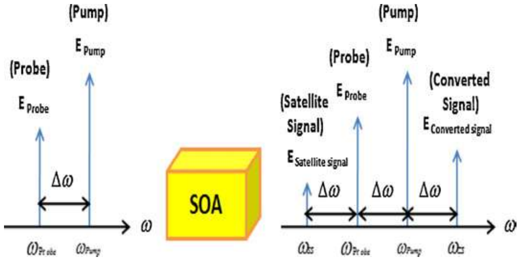

Fig. 1. FWM scheme in SOA.

due to the frequency response of the SOA nonlinearity. The conversion efficiency of FWM has been shown to depend on various factors – three of which are pump frequency, signal frequency and the size of the active region of the SOA. The wavelength-dependent gain and phase interference within the FWM mechanism causes the down-conversion efficiency to be slightly higher than the up-conversion efficiency. Increasing the gain, saturation power and carrier recovery rate of an SOA are a few practical methods of improving the conversion efficiency of a FWM wavelength converter [5].

$$\eta = 10\log\frac{P_{\text{out}}(\lambda_{\text{converted\_signal}})}{P_{\text{in}}(\lambda_{\text{pump\_signal}})} \quad (1)$$

Studies on FWM-based wavelength converters in SOAs have been proposed in much previous work, due to the numerous advantages offered by the nonlinearities of the SOA. D'Ottavi et al. proved that the use of a long SOA could improve the performance of wave mixing converting at a data rate of 10 Gb/s [6]. Also, Hsu et al. claimed that higher conversion efficiency and wider conversion range can be achieved by applying an assisted holding beam into the SOA [7]. This technique is also capable of converting multiple wavelengths, which had been proposed by Contestabile et al. in which a scheme of 16 simultaneous WDM signals was produced and transmitted at a data rate of 10 Gb/s [8].

2. Modeling and simulation

The simulation was carried out at a central frequency of 193.5 THz. A scheme of the modeling blocks was created, based on a CW laser source for the FWM-based wavelength converter, and is shown in Fig. 2. The SOA parameters used are shown in Table 1. The pump and probe from the CW laser source were set to have SOA input powers of 5 dBm and 3 dBm respectively. The probe signal was modulated by a NRZ electrical driver, with a 2^7-1 PRBS signal at a data rate of 2.5 Gb/s. The signal wavelength was varied in accordance with the desired detuning frequency. The pump and probe signals each passed through individual polarization controllers, PC1 and PC2, in order to match the state of polarization between them. This was a necessary condition to ensure efficient FWM occurred in the SOA before being combined by the 3 dB coupler.

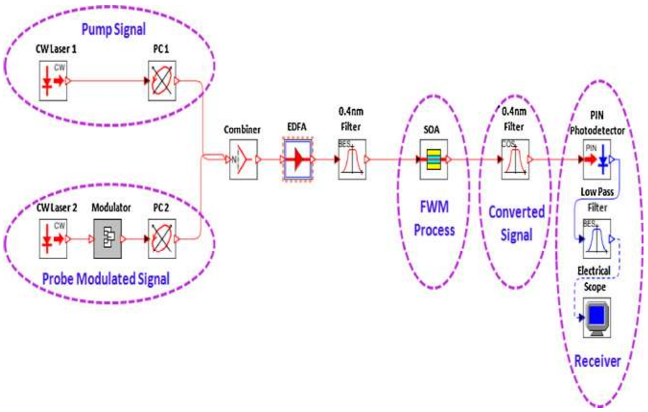

Fig. 2. Simulation schematic for FWM wavelength converter.

Table 1
Physical SOA parameters.

Parameter	Symbol	Value/unit
Carrier density at transparency	N_0	1.0×10^{24} m^3
Internal waveguide scattering loss	α_s	10.5×10^2 m
Material gain	a	3×10^{-20} m^2
Length	L	300×10^{-6} m
Width	W	1.5×10^{-6} m
Thickness	D	0.15×10^{-6} m
Confinement factor	Γ	0.35
Light frequency	w_0	193.5 THz
Bias current	I	250 mA
Saturation power	P_s	9.616 dBm

The combined signals were then amplified by an erbium doped fiber amplifier (EDFA), having a fixed gain of 10 dB and with an average noise figure of 4.2 dB. The EDFA was used to increase the combined signal power in order to saturate the SOA. A 0.4-nm bandwidth optical band-pass filter (BPF) was placed just after the EDFA so that any additional ASE outside the signal bandwidth was suppressed, hence increasing the OSNR of the converted signal. A nominal bias current of 250 mA was injected into the SOA as soon as the combined signals entered it, which then generated the converted signal through the FWM process. Another 0.4-nm BPF, placed just after the SOA and centered on the converted signal wavelength, ensured clean capture of the converted wave with complete pump and original signal removal.

3. Results and discussions

The simulation has been carried out for the set-up shown in Fig. 2. The converted signal power obtained as a function of wavelength shift is shown in Fig. 3. The pump signal wavelength was fixed at 1550 nm, while the probe signal wavelength was varied in the range 1551–1555 nm for down-conversion and 1535–1549 nm for up-conversion. Down and up conversions refer to the converted wavelength, which is either lower or higher than the pump signal wavelength respectively. From Fig. 3, it can be seen that further the signal is converted, lower is the power of the converted signal. Both down and up conversions give almost similar readings at lower detuning wavelengths. However, a slight difference was observed at higher detuning of more than 6 nm, whereby down-conversion gave better performance compared to up-conversion. This was due to the partially destructive or constructive phase interference between the FWM mechanisms.

Conversion efficiency and optical signal-to-noise ratio are usually the two most commonly cited figures of merit for the converted wave, and both need to be highly considered in the design of any wavelength converter. Conversion efficiency is defined as the ratio of the converted signal power to the probe signal power (dB). However, an optimum value of the optical signal to noise ratio

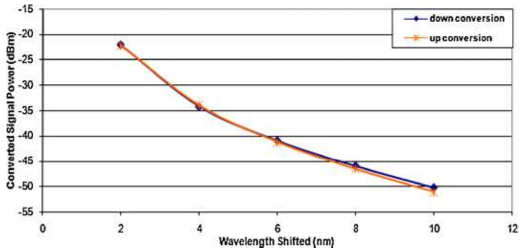

Fig. 3. Converted power for down and up conversions.

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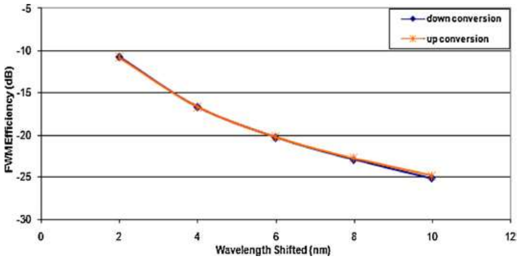

Fig. 4. FWM efficiency for down and up conversions.

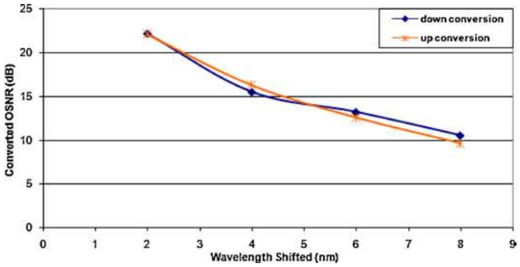

Fig. 5. Converted OSNR for down and up conversions.

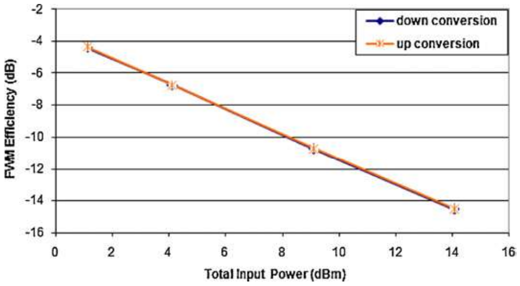

Fig. 6. FWM efficiency for 2 nm conversion.

(OSNR) does not necessarily indicate optimum conversion efficiency. Figs. 4 and 5 show the FWM efficiency and converted OSNR for both down and up conversions respectively. The conversion efficiency and converted OSNR both decrease at large detuning wavelengths, due to the frequency response of the non-linear process. It can also be seen, for example, that both up and down conversions experience a conversion efficiency decrease from about −10 dB to −25 dB, and a converted OSNR decrease of about 25 dB to 10 dB, both for a 10 nm wavelength shift.

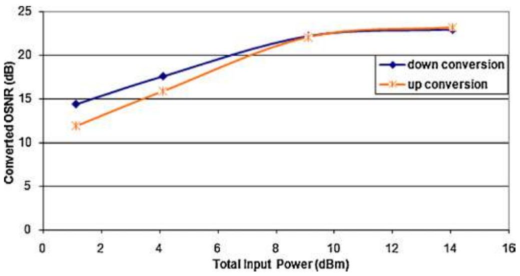

Fig. 7. Converted OSNR for 2 nm conversion.

Figs. 6 and 7 show the conversion efficiency and converted OSNR, respectively, as a function of total SOA input power for 2 nm up and down conversions. It can be observed that an increase in total SOA input power (i.e. pump plus probe) will increase the SOA level of saturation, and therefore decreases the conversion efficiency, but steadily increases the OSNR. Therefore, to enable efficient FWM to occur in the SOA, maximum OSNR can be obtained by operating the SOA in deep saturation, while sacrificing the conversion efficiency. Based on previous measurements of the gain characteristics of the actual SOA used here, the saturation power is about 9.6 dBm.

4. Conclusions

We have simulated and investigated various effects of the FWM wavelength conversion process occurring within a SOA medium, and have gathered useful data which could be used to evaluate the potential of such a scheme for applications in future, all-optical converter systems. The analysis was done by varying the wavelength shift and the power of the probe signal. The conversion efficiency, converted signal power and converted OSNR have been analyzed. It was found that the greater the conversion bandwidth, the lower was the power gained by the converted signal. Furthermore, both the conversion efficiency and converted OSNR decreased at large detuning wavelengths, due to the frequency response of the non-linear process. Also, higher total SOA input powers were shown to increase saturation and therefore decrease conversion efficiency, while steadily increasing the OSNR.

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References

[1] D.D. Marcenac, D. Nesset, A.E. Kelly, D. Gavrilovic, 40 Gb/s transmission over 103 km of NDSF using polarization independent mid-span spectral inversion by four-wave mixing in a semiconductor optical amplifier, Electron. Lett. 34 (1) (1998) 100–101.
[2] S. Singh, R.S. Kaler, 20-Gb/s and higher bit rate optical wavelength conversion for RZ-DPSK signal based on four-wave mixing in semiconductor optical amplifier, J. Fiber Integr. Optics 26 (5) (2006) 295–308.
[3] S. Singh, R.S. Kaler, Wide band optical wavelength converter based on four-wave mixing using optimized semiconductor optical amplifier, J. Fiber Integr. Optics 25 (3) (2007) 213–230.
[4] R.D.O. Ribeiro, M.J. Pontes, M.T.M.R. Giraldi, M.C.R. Carvalho, Characterisation of all-optical wavelength conversion by cross-gain modulation of ASE on a SOA, in: International Microwave and Optoelectronics Conference Proceedings, 2005, pp. 218–221.
[5] S.L. Lee, P.M. Gong, C.T. Yang, Performance enhancement on SOA-based four-wave-mixing wavelength conversion using an assisted beam, IEEE Photon. Technol. Lett. 14 (12) (2002) 1713–1715.
[6] A. D'Ottavi, P. Spano, G. Hunziker, R. Paiella, R. Dall'Ara, G. Guekos, K.J. Vahala, Wavelength conversion at 10 Gb/s by four-wave mixing over a 30-nm interval, IEEE Photon. Technol. Lett. 10 (7) (1998) 952–954.
[7] D. Hsu, S. Lee, P. Gong, Y. Lin, S.S.W. Lee, M.C. Yuang, High-efficiency wide-band SOA-based wavelength converters by using dual-pumped four-wave mixing and an assist beam, IEEE Photon. Technol. Lett. 16 (8) (2004) 1903–1905.
[8] G. Contestabile, M. Presi, E. Ciaramella, Multiple wavelength conversion for WDM multicasting by FWM in an SOA, IEEE Photon. Technol. Lett. 16 (7) (2004) 1775–1777.

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