Wavelength converter solutions with semiconductor optical amplifiers

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Keywords: wavelength conversion, semiconductor optical amplifier (SOA), cross-gain modulation (XGM)

Semiconductor Optical Amplifiers (SOA) offer several possible solutions for wavelength conversion in the optical domain. In this paper different possible solutions are compared, pointing out the advantages and disadvantages of each. Then a simple and at the same time most promising method, the Cross-Gain Modulation (XGM) is investigated through performance measurement results.

Introduction

The main functions of optical telecommunication networks are the multiplexing and the routing of the information channels. The most widespread solution for optical networking is represented by the WDM (Wavelength Division Multiplexed) networks.

In these networks, channels can be separated and handled according to their wavelength, so that they can be transmitted through the same optical fiber. Connections can be simply point-to-point, but also complex network hierarchies can be built. In the second case it is essential, that for easy channel routing and to avoid wavelength collision at any point of the network, to make wavelength conversion possible at each node of the network, in order to transmit the same channel at different wavelengths on different links of the transmission route.

Nowadays the applied devices for wavelength conversion purposes are optoelectronic units. This means that the device converts the optical signal to the electrical domain – also regenerates it –, and retransmit it on an other wavelength. The advantages of this devices, that their technology is mature and they are available for trial use. But in optical networking aspect the long-term disadvantages of them is the opto-electronic conversion, which limits the possible operation speed (due to physical properties) and makes the device dependent on the signal coding scheme (not transparent for optical signals).

The main efforts in optical researches are therefore focused on *transparent* optical solutions. Though these solutions are mostly available only in laboratory environment, the possible performance of these devices according to the demonstrated results are really promising [1,2]. In the first part of this article we give an overview of the state-of-the-art of wavelength conversion using *semiconductor optical amplifiers* (SOA), than one of the possible methods is presented in details and investigated through measurement results.

Wavelength conversion methods

Wavelength converters should meet several requirements. They should operate at the 10 to 100 GHz range or even higher, and in order to build long-haul connections they should be cascadable. Further need is the low complexity of the device, high output power and fast tunability.

Optical gating methods

With this overall name we refer to those *all-optical* methods, where the new wavelength continuous wave (CW) signal is provided by an external source, and another device is applied to modulate the intensity of this signal according to the incoming optical information signal. The most typical solutions from this category are shown in the next subsection.

As it is widely known, in semiconductor optical amplifiers the key physical phenomenon is the population inversion, in other words the carrier density on the higher energy level in the active region. This carrier density is provided by external electrical pump. This population inversion gives the optical amplification in the amplifier due to stimulated emission. But through the manipulation of the carrier density by an optical signal (due to gain saturation process) it can also be applied for wavelength conversion.

The following methods use the device in this way.

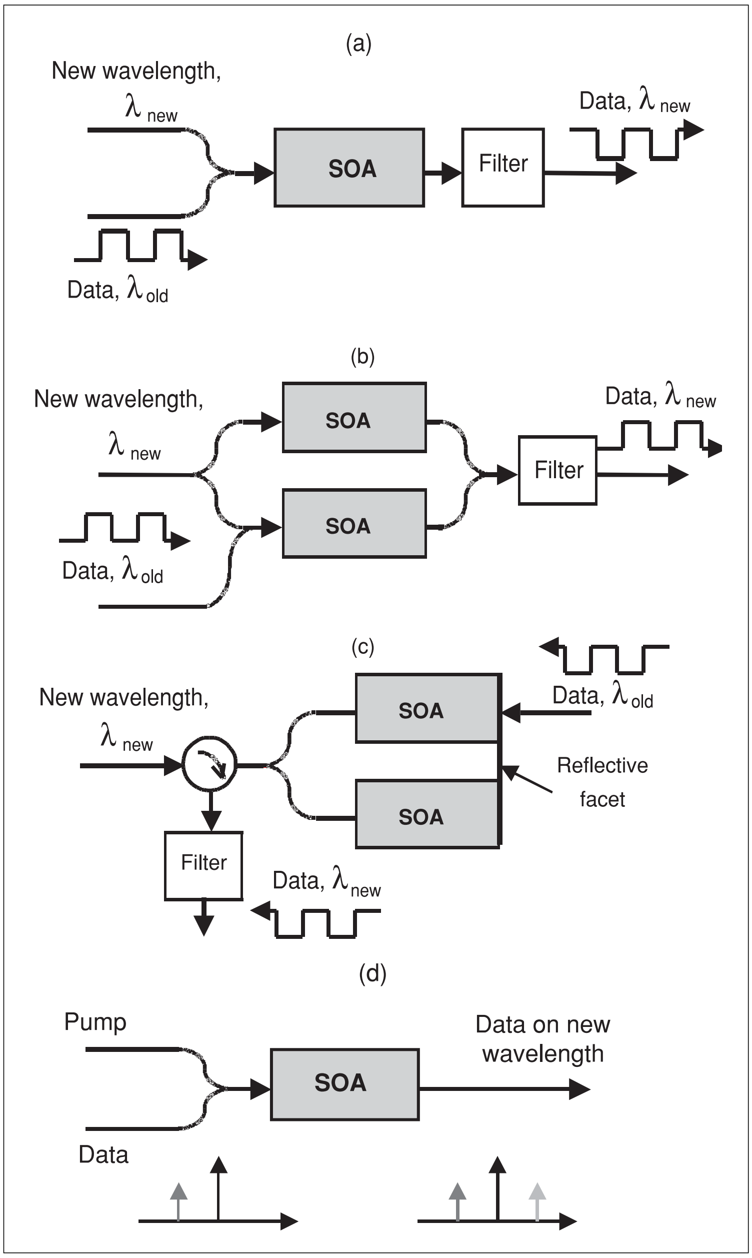
Cross-gain modulation (XGM)

In this case the basis of the wavelength conversion is the gain saturation itself. The external pump source has a constant pump rate, and so the output power of the SOA is also limited. Therefore there is a limit in the incident optical power of the information signal, called the saturation power, until the SOA provides constant gain, above it the gain will significantly decrease. As the material is homogenous, the SOA will saturate at the whole operation wavelength spectrum, so that the same gain variation will be for the CW signal at the new wavelength. In this way the CW signal will be modulated according to the input optical signal. The block scheme of the device is shown in *Fig. 1/a.*

The gain of the SOA is inversely proportional to the intensity of the incoming signal, thus it will work as an external modulator for the CW signal [3,4,5].

The advantages of this method are the simplicity of the device and the high transfer speed (approximately 100 GHz, limited by the carrier recovery time). But there are also some disadvantages. The input optical signal power should be high enough to saturate the SOA, a tuneable optical filter is needed in order to suppress the old wavelength, and the device inverts the signal levels (however the last two features can be avoided by special arrangements). And last but not least, this method is only suitable for conversion of intensity modulated signals, as the phase information is lost during the process. We investigate this method in details later in this article.

Fig. 1. Wavelenght converter schemes
a) XGM
b) XPM Mach-Zender interferometer
c) XPM Michelson interferometer
d) Wave mixing



Cross-Phase Modulation (XPM)

Placing two SOAs in the arms of an interferometer, it can also work as a wavelength converter. The CW signal at the new wavelength is transmitted into both arms, and the information signal to one of them. The intensity modulation of the information signal will lead to variation in the carrier density, and in the same time in the refractive index. The variation of the refractive index will result in variation in propagation time, which gives a phase difference between the two arms. This phase modulation can be converted to intensity modulation by an interferometer structure. Typically a Mach-Zender *(Fig. 1/b.)* or a Michaleson-interferometer *(Fig. 1/c.)* is used.

Compared to the XGM this interferometric scheme provides signal quality improvement. A stable operation can be achieved by integrating the interferometer to a single semiconductor chip, so that the two SOAs can operate at same conditions [6,7,8,9].

The possible operation speed is around 100 GHz, but 168 GHz has also been demonstrated.

Cross-polarisation Modulation (XPolM)

Wavelength conversion can be achieved through changing the polarisation of the CW signal at the new wavelength [10].

In this case we utilise a *polarisation beam splitter* (PBS), and its capability to filter optical signals according to their polarisation state. First the CW signal is transmitted through a SOA and adjusted to a PBS, so that the whole signal is transmitted through the system. Than the intensity modulated information wavelength is also transmitted into the SOA, and due to it birefringence the intensity variation will cause a polarisation rotation on the CW signal. This polarisation modulation will be converted into intensity modulation by the PBS.

The main advantage of this method is the high achievable extinction ratio, but the complexity of the device makes its application problematic.

Wave mixing

The earlier mentioned all-optical and transparent optical transmissions are not synonyms to each other. The gating methods are not transparent solution, as the only preserve the intensity information of the signal.

In this case we utilise the nonlinear behaviour of the SOAs, and the new wavelength signal is produced as the nonlinear combination of the input signals. Thus, if any of the input signals contains intensity, phase or polarisation modulation, it will be represented in the output signal. In this way, wave mixing is the only method with transparent optical properties, because all the optical properties of the information signal are unchanged during the conversion.

According to the number of the input signals there is *four-wave mixing* (FWM), *three-wave mixing* (TWM) and *difference frequency generation* (DFG), depending which order of nonlinearity is utilised.

In addition to transparency wave mixing is the only method which allows parallel conversion of more than one channel and capable for operating over 100 GHz. But on the other hand the optical nonlinear efficiency is very low, thus the implementation of this converters is complicated.

Investigation of XGM

After the general overview we investigate the most promising method of wavelength conversion, the cross-gain modulation. We studied XGM through simulation and measurements, and present the most important results in this article.

Saturation process

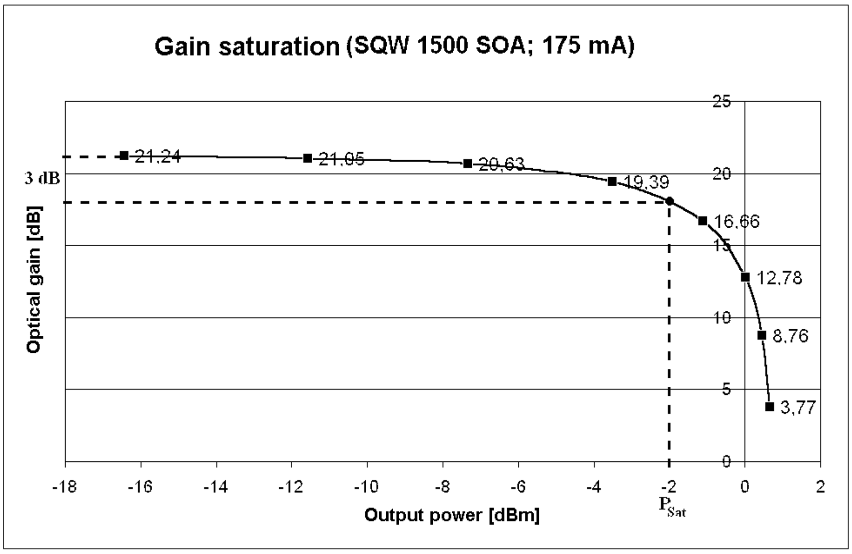
The most important process in semiconductor optical amplifiers in the cross-gain modulation aspect is the saturation.

As we mentioned earlier, population inversion is provided by an external electrical supply, which pumps carriers to the active region at constant rate. This carrier density is consumed by optical amplification through stimulated emission. When the input optical power is high than, to provide the optical gain, high output power is needed. Above a certain limit, the desired output power can not be provided by the SOA (because of the limited pump power), so the population inversion in the device and thus the gain will decrease.

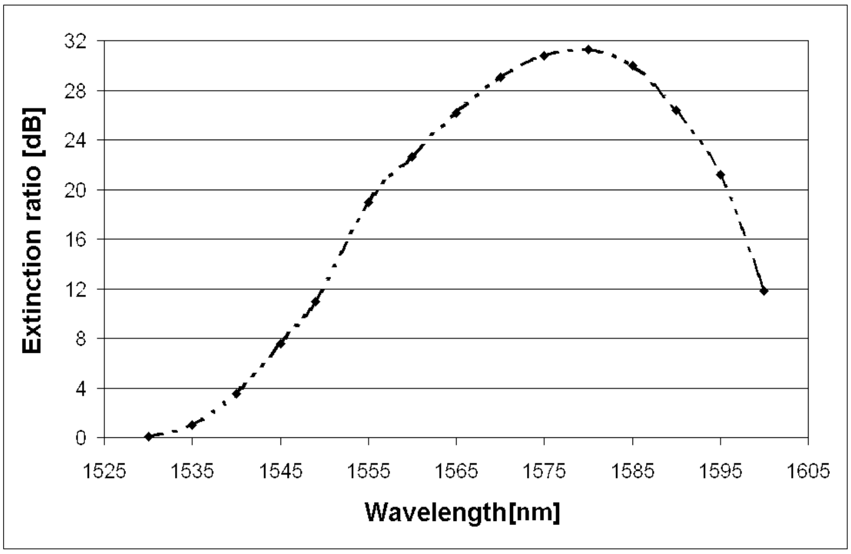
Plotting the optical gain versus the output optical power we get the saturation characteristic of the SOA, which is shown for the measured device in *Fig. 2.* It can be seen in the figure, that for a wide range of the optical power the SOA provides almost constant gain. The saturation power is defined by the 3 dB threshold, which is also shown in the figure. The maximum output power can also be estimated according to the figure.

As a normal amplifier constant gain for all intensities is preferred, for linearity reasons. But in our case it is desired to have big variation in the gain value due to the variation of the input optical signal, in order to have high extinction ratio. The low value of the saturation power is also advantageous, so that signals with low intensity can also be converted. This can be influenced by the material and the layer construction of the amplifier.

Fig. 2.
a) Gain saturation



b) Extinction ratio vs. wavelenght (SQW 1500 SOA, λ_{new}=1552 nm)



Extinction ratio measurements

Besides several interesting parameters *extinction ratio* is the most important one, as it highly determines the quality of the converted signal. Extinction ratio is defined by the quotient of the maximum and minimum optical signal power, and it depends on the maximal achievable gain variation due to saturation. Measured extinction ratio versus the wavelength

The wavelength dependence clearly comes from the band structure, and the broadening of the energy levels in the semiconductor crystal. The measured device was designed to operate over the WDM wavelength range, and provides sufficient extinction ratio over the whole range. The maximal value for extinction was measured on the wavelength of 1582 nm and it was over 30 dB.

The operation speed is depends on the carrier recovery lifetime in the active region of the SOA. The typical value for this is around 1 ps, which allows operation up to 100 GHz. This, compared to the electrical devices, which are estimated to be limited at 40 GHz due to physical reasons, means that cross-gain modulation can be used for broadband telecommunication applications in the future.

Conclusions

Wavelength conversion using semiconductor optical amplifiers is one of the most intensively developing topic of optical telecommunication research. As it was shown, several approaches exist, with advantages and disadvantages. Up to the present matured, commercially available solutions are represented only by optoelectronic devices, but in long terms the increasing bandwidth requirements can be fulfilled only using all-optical, or rather optically transparent devices. Which method will be the winner? Device fabrication prices and market demands will decide.

References

[1] T. Durhuus, B. Mikkelsen, C. Joergensen, S.L. Danielsen, K.E. Stubkjaer: “All-optical wavelength conversion by semiconductor optical amplifier”, IEEE/OSA J. Lightwave Technology, vol.14, pp.942–952, 1996.

[2] S. J. B. Yoo: “Wavelength conversion technologies for WDM network applications”, IEEE/OSA J. Lightwave Technology, vol.14, pp.955–966, 1996.

[3] Derek Nesset, Tony Kelly, Dominique Marcenac: “All-Optical Wavelength Conversion Using SOA Nonlinearities”, IEEE Communications Magazine, December 1998, pp.56–61.,

[4] A. Carena, M. D. Vaughn, R. Gaudino, M. Shell, Daniel J. Blumenthal: ”OPERA: An Optical Packet Experimental Routing Architecture with Label Swapping Capability”, JLT, vol.16, no.12, pp.2135–45, December 1998

[5] S. J. B. Yoo, Hyuek Jae Lee, Zhong Pan, Jing Cao, Yanda Zhang, Katsunari Okamoto, Shin Kamei: ”Rapidly Switching All-Optical Packet Routing System With Optical-Label Swapping Incorporating Tunable Wavelength Conversion and a Uniform-Loss Cyclic Frequency AWGR”, PTL, vol.14, no.8, pp.1211–13, 2002.

[6] R. G. Broeke, J. J. M. Binsma, M. van Geemert, F. Heinrichsdorff, T. van Dongen, J.H.C. van Zantvoort, E. Tangdiongga, H. de Waardt, X. J. M. Leijtens, Y. S. Oei, M. K. Smit: “An All-Optical Wavelength Converter in a Layer-Stack Suitable for Compact Photonic Integration”, Proceedings Symposium IEEE/LEOS Benelux Chapter, Amsterdam, pp.95–98, 2002.

[7] J. Leuthold, G. Raybon, Y. Su, R. Essiambre, S. Cabot, J. Jaques, M. Kauer: “40 Gbit/s transmission and cascaded all-optical wavelength conversion over 1,000.000 km”, El. Lett., vol.38, no.16, pp.890–892, August 2002

[8] Min-Yong Jeon, Dong Sung Lim, Hak Kyu Lee, Joon Tae Ahn, Do Il Chang, Kyong Hon Kim, Seung Beom Kang: “All-Optical Wavelength Conversion for 20-Gb/s RZ Format Data”, Photonics Technology Letter, vol.12, no.11, IPTLEL (ISSN 1041–1135) pp.1528–30, November 2000

[9] J. Leuthold, C. H. Joyner, B. Mikkelsen, G. Raybon, J. L. Pleumeekers, B. I. Miller, K. Dreyer, C. A. Burrus: “100Gbit/s all-optical wavelength conversion with integrated SOA delayed-interference configuration”, Electronics Letters, vol.36, no.13, pp.1129–30, June 2000

[10] Y. Liu, M. T. Hill, E. Tangdiongga, H. de Waardt, N. Calabretta, G. D. Khoe, H. J. S. Dorren: “Wavelength Conversion Using Nonlinear Polarization Rotation in a Single Semiconductor Optical Amplifier”, IEEE Photonics Technology Letter, vol.15, no.1, January 2003

[11] J. P. R. Lacey et al.: “Four-channel polarization insensitive optically transparent wavelength converter,” IEEE Photon. Tech. Lett., vol.9, no.10, pp.1355–57, 1997.

[12] D. D. Marcenac et al.: “40Gb/s transmission over 103 km of NDSF using polarization independent mid-span spectral inversion by four wave mixing in a semiconductor amplifier,” Elect. Lett., vol.34, no.1, pp.100–101, 1998.

[13] R. G. Batchko, R. Roussev, M. H. Sher, L. R. Marshall: “All-Optical MgO:$LiNbO_3$ Wavelength Converter for Telecommunications”,

[14] M. C. Cardakli, A. B. Sahin, O. H. Adamczyk, A. E. Willner, K. R. Parameswaran, M. M. Fejer: “Wavelength Conversion of Subcarrier Channels Using Difference Frequency Generation in a PPLN Waveguide”, IEEE Photon. Tech. Lett., vol.14, no.9, pp.1327–29, September 2002