The Enhanced Functionalities of Semiconductor Optical Amplifiers and their Role in Advanced Optical Networking

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I. Introduction

The Semiconductor Optical Amplifier (SOA) is a highly versatile component that can be deployed for a wide range of amplification and routing functions within the telecommunications industry. The minimal space requirements, integration capability, and strong potential for cost reduction through scaled manufacturing processes will ensure that the SOA plays an increasingly important role in future advanced optical networks. SOAs are a cost-effective solution to implementing optical amplification in advanced optical networking subsystems for core, metro, and ultimately access applications. Commercialized SOAs are available now from InPhenix.

Coarse wavelength division multiplexing (CWDM) is a low cost route for providing connection flexibility and increased throughput for metro and enterprise network layers. Extending the capacity and distance of CWDM systems (>100 km) requires a low cost optical amplifier operating across the entire optical bandwidth (from 1260 nm to 1620 nm). The SOA is the only viable technology available today that can be deployed to meet these expanding applications.

The fast nonlinear characteristics of SOAs are very attractive for a number of applications such as optical signal processing, clock recovery, ultra fast optical time multiplexing/demultiplexing, pulse shaping, optical routing, dispersion compensation and wavelength conversion in WDM applications.

SOAs can be used for gating optical signals, i.e. signals can be either amplified or absorbed by SOAs. The blocking properties of SOAs at low bias currents are extremely useful because they enable channel routing functions, such as reconfigurable add/drop multiplexers (ROADM), to be produced with off-channel isolation better than 50 dB. Due to their nonlinear characteristics, SOAs can be used to convert an optical signal to another wavelength by Cross-Gain Modulation (XGM), Cross-Phase Modulation (XPM) or Four-Wave Mixing (FWM) to achieve all-optical cross-connects without OEO conversion. XPM can be used to provide 2R (re-amplification, pulse reshaping) or 3R (re-amplification, pulse reshaping and retiming) regenerations. SOAs can provide a cost-effective solution that is physically small and has tremendous potential for integration with a wide variety of active and passive components.

In this paper, we will review some SOA fundamentals and their associated enhanced functionalities including wavelength conversion, re-configurable optical add/drop, optical cross-connects, and all-optical regeneration in advanced optical networking.

II. SOA Fundamentals

An SOA is essentially a laser diode (LD) with no feedback from its input and output ports and hence is also referred to as a Traveling-Wave Amplifier (TWA). SOAs have proven to be a versatile and multifunctional device that will be a key building block for future optical networks. There are five parameters used to characterize SOAs:

Gain (G_s),
Gain Bandwidth,
Saturation Output Power (P_{sat}),
Noise Figure (NF),
Polarization Dependent Gain (PDG)

An SOA should have the highest gain appropriate to the application. A wide optical bandwidth is also desirable so that the SOA can amplify a wide range of signal wavelengths. Gain saturation effects introduce undesirable distortion to the output so an ideal SOA should have very high saturation output power to achieve good linearity and to maximize its dynamic range with minimum distortion. An ideal SOA should also have a very low noise figure (the physical limit is 3 dB) to minimize the amplified spontaneous emission (ASE) power at the output. Finally, an ideal SOA should have very low polarization sensitivity to minimize the gain difference between the transverse-electric (TE) and transverse-magnetic (TM) polarization. However, an ideal SOA is impossible to realize because of the physical limitations of the various processes taking place inside it.

Gain

SOAs amplify incident light through stimulated emission; the same mechanism used by semiconductor lasers. An optical amplifier is essentially a laser without feedback. Its most useful feature is the optical gain realized when the amplifier is pumped to achieve population inversion. The optical gain depends not only on the frequency (or wavelength) of the incident signal but also on the local beam intensity at any point inside the amplifier.

The single pass optical gain (G_s) below saturation is approximately determined by:

$$G_s \propto e^{\Gamma(g_m-\alpha)L} = e^{\Gamma[g_0(N-N_0)-\alpha]L} = e^{\Gamma\left[g_0\left(\frac{\eta_i I \tau_s}{eLwd}-N_0\right)-\alpha\right]L} \tag{1}$$

Where spectral effects and nonuniform distribution of the carrier density are not considered.

Γ is the optical confinement factor,
g_m is the material gain,
α is optical loss,
L is the cavity length,
W is the active width,
d is the thickness of the active region in which the carriers are confined,
e is the electronic charge,
g_0 is the gain coefficient,
η_i is the current injection efficiency,
I is the operating current,
N is the carrier density at the operating current I,
N_0 is the carrier density at transparency,
τ_s is the spontaneous recombination lifetime of the carriers.

Fig 1 Chart A

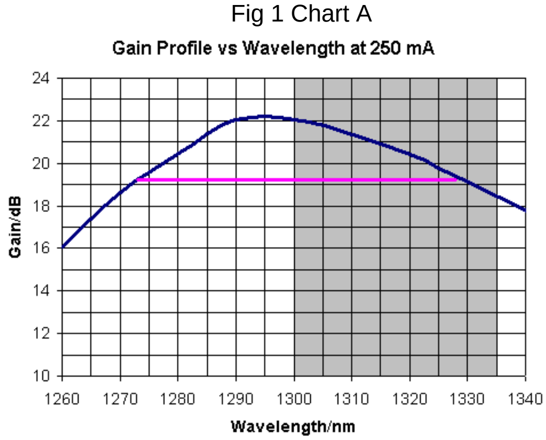


Fig 1 Chart B

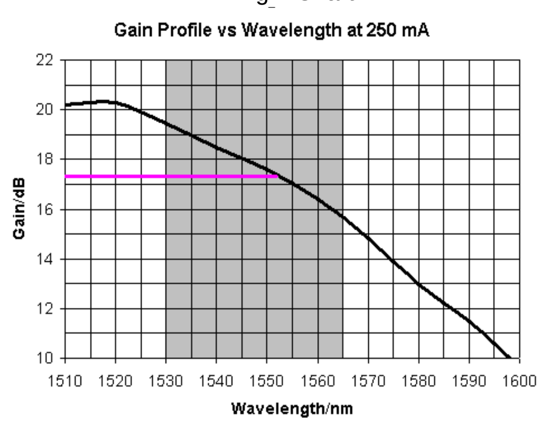


Figure 1 charts the typical gain profile versus wavelength at 250 mA for:

(A) IPSAD1301: a 1310 nm gain type SOA where the red line represents a 3dB gain bandwidth (55 nm) and the shadow area is the wavelength operating range for the best performance in terms of high P_{sat} and low NF.

(B) IPSAD1501: a 1550 nm gain type of SOA where the red line represents a 3dB gain bandwidth (>45 nm) and the shadow area is the wavelength operating range for the best performance in terms of high P_{sat} and low NF.

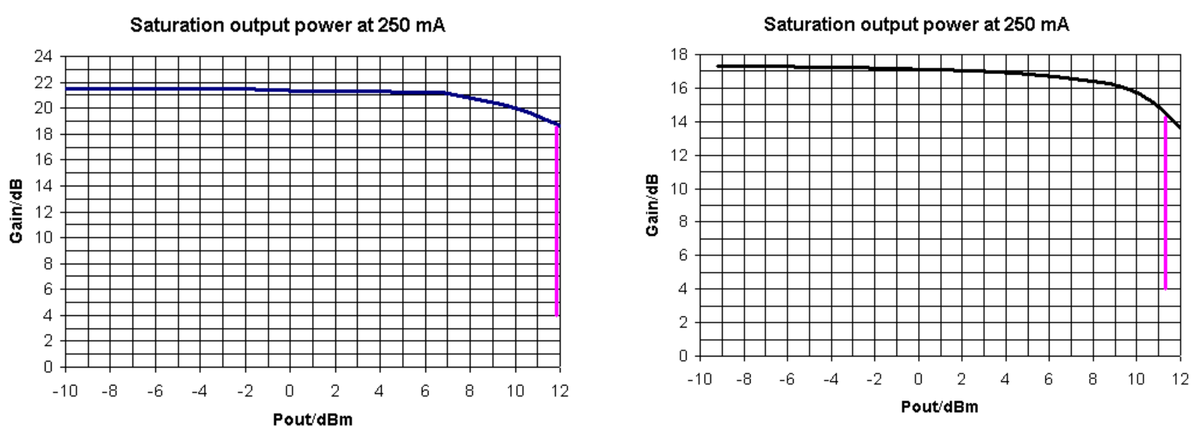
Equation (1) indicates that a high gain may be achieved with a high injection current, a large optical confinement, a long cavity, a multiple quantum well (MQW) structure, or a combination of them. Fig. 1 shows the typical gain profile versus wavelength at 250 mA for IPSAD1301 and IPSAD1501 gain type SOAs from InPhenix.

Gain Bandwidth

The gain bandwidth is defined as the full width at the half-maximum (FWHM) height of the gain spectrum. Amplifiers with a relatively large bandwidth are preferred for optical communication systems since the gain is then nearly constant over the entire bandwidth. A 3dB bandwidth is about 45 nm for bulk SOAs and it can exceed 60 nm for quantum-well SOAs. In general, the bandwidth depends inversely on the optical confinement and the cavity length and it will broaden as the injection current increases due to the band filling effect. In addition, MQW SOAs provide wider bandwidth with respect to bulk SOAs. Figure 1 shows a typical 3dB gain bandwidth at 250 mA for IPSAD1301 and IPSAD1501 gain type SOAs from InPhenix.

Saturation Output Power

The origin of gain saturation lies in the power dependence of the gain coefficient where the population inversion due to injection current pumping is reduced with the stimulated emission induced by the input signal. Of practical interest is the saturation output power, which is defined as the output power for which the amplifier gain is reduced by a factor of 2 (or by 3 dB) from its unsaturated value. In general, the saturation output power depends inversely on the optical confinement. Fig. 2 shows the typical saturation output power at 250 mA for InPhenix IPSAD1301 and IPSAD1501 gain type SOAs.



(a) (b)

Fig. 2 Typical saturation output power as shown by the red line at 250 mA for:
(a) IPSAD1301: 1310 nm gain type SOA where Psat=11.85dBm at 1310 nm.
(b) IPSAD1502: 1550 nm gain type SOA where Psat=11.3dBm at 1550 nm.

Noise Figure

All laser amplifiers degrade the signal-to-noise ratio (SNR) of the amplified signal because of spontaneous emissions that add to the signal during its amplification. The SNR degradation is quantified through a parameter F_n, called the amplifier noise figure and defined as $(SNR)_{in}/(SNR)_{out}$. The noise is mainly attributed to the following sources:

(1) Amplified signal shot noise,
(2) Spontaneous emission shot noise,
(3) Signal-spontaneous beat noise,

(4) Spontaneous-spontaneous beat noise,
(5) Signal excess noise

Items (1) and (2) are related to several detector parameters. Usually the beat noise levels are 20 dB larger than the shot noise. In the high output power region the signal-spontaneous beat noise dominates, while in the low output power region the spontaneous-spontaneous beat noise prevails. For an ideal detector whose performance is limited by the shot noise only, the SNR of the amplified signal is degraded by a factor of 2 (or 3 dB). The SOA has the same theoretical lower noise figure limit of 3 dB as an EDFA. However, in practice an SOA exhibits a higher noise level due to its intrinsic internal loss and the lower coupling efficiency on its input side. For most SOAs, F_n is typically in the range of 6-10 dB.

For optical communication systems, an optical amplifier should have an F_n as low as possible. NF is also dependent on the operating wavelength, the operating current, and the input signal power. Through careful design of the MQW active layer and the waveguide, InPhenix has developed an SOA with a very small NF dependence on the operating wavelength and current over a wide range. Fig.3 shows the performance of this type of SOA where a small noise figure dependence on the operating wavelength and current is achieved with a wide wavelength (1280 nm to 1340 nm) and a wide operating current (150 mA to 350 mA).

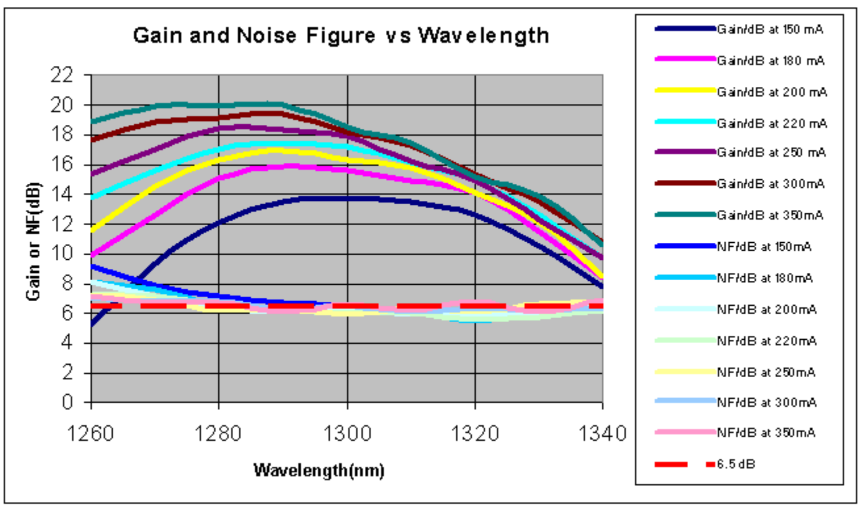


Fig .3 Gain and Noise Figure vs. Wavelength for an InPhenix IPSAD1301 SOA measured at 150mA to 350mA.

Polarization Sensitivity

An undesirable characteristic of SOAs is their gain sensitivity to input signal polarization. The amplifier gain differs for the transverse-electric (TE) and transverse-magnetic (TM) polarizations because the confinement factor and the effective mode index are different for each of them. This feature makes the amplifier gain dependent on the polarization state of the input beam, a property undesirable for light wave system applications where the polarization state changes with propagation along the fiber. Several possible approaches in geometric design of the active layers combined with a proper use of tensile strain (bulk or multi-quantum well) can reduce the polarization sensitivity of SOAs to less than 1 dB.

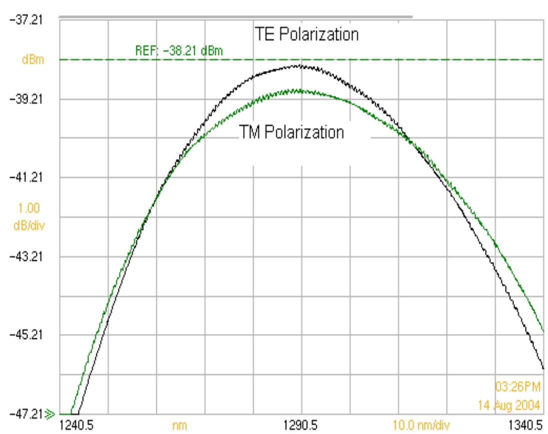


Fig. 4 ASE spectrum power for TE and TM polarization at 250mA measured on an InPhenix IPSAD1301 SOA.

Fig. 4 shows a typical ASE spectrum for TE and TM polarization observed at 250 mA where the peak wavelength difference between TE and TM is less than 1 nm. ASE power density difference between TE and TM polarization is less than 0.8 dB over the wavelength range from 1240 nm to 1340 nm indicating that polarization dependent gain is well controlled at less than 1 dB.

Two other parameters are also used to characterize an SOA:

(1) **Gain Ripple**,
(2) **Switching Time**

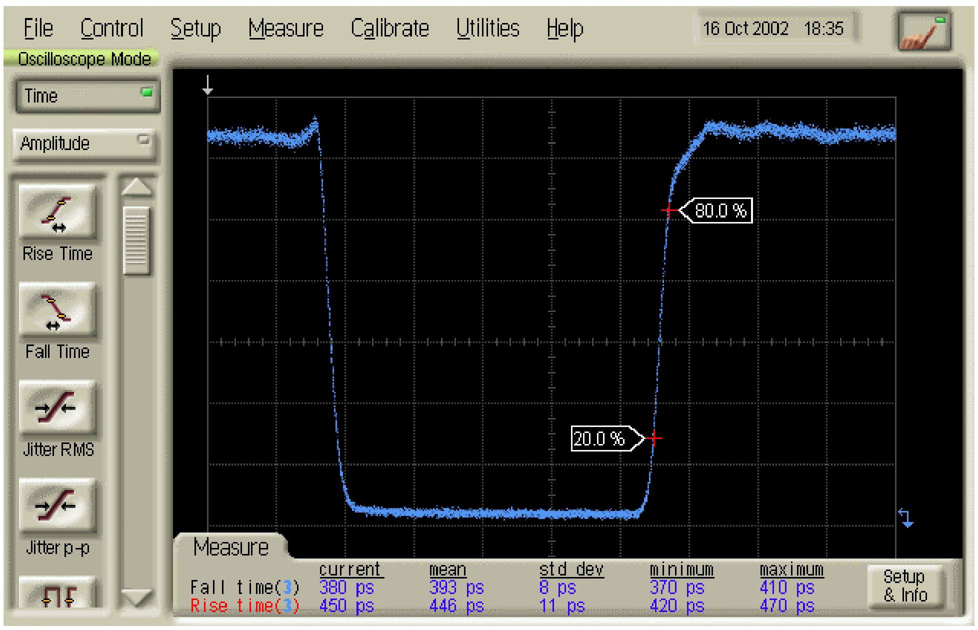


Fig. 5 Typical switching time for IPSAD1302 and IPSAD1502 SOA Devices

SOA **Gain Ripple** is caused by residual reflections from the SOA facets and should be as low as possible. In general, the facet reflectivity of an SOA device should be 0.01% or less to achieve a 20 dB gain.

The SOA **Switching Time** is measured as rise time and fall time, the typical switching time is in the order of nanoseconds. Switching time is a critical parameter when the SOA is used as switching function. Fig. 5 shows the typical switching time for InPhenix IPSAD1302 and IPSAD1502 devices where the rise time (from 20% to 80%) and fall time (from 80% to 20%) is about 500 picoseconds.

III. Wavelength Conversion Based on SOAs

All-optical wavelength conversion will become an essential function in future all-optical networks and photonic switching blocks. This feature can be realized through one of three techniques:
(1) Cross-Gain Modulation,
(2) Cross-Phase Modulation,
(3) Four-Wave Mixing using SOAs.

Wavelength Converters Based on Cross-Gain Modulation (XGM)

Amplification of an Input signal results in the carrier density depletion in an SOA. Optical gain in an SOA can be reduced by this carrier density depletion in high input power applications. This phenomenon distorts the transmitted signal for SOAs used as in-line amplifiers but it can be used to realize optical wavelength conversions (WCs). For this purpose, two signals, Pump (input signal, λ_S) and Probe (converted output signal, λ_C), are simultaneously injected into an SOA. The pump signal is amplitude modulation (AM) format while the probe is a continuous wave (CW).

When the Pump is in a low power state the SOA will not be saturated and therefore the probe will experience unsaturated gain. In a high power state the gain is saturated and the probe signal will experience a lower gain. The degree of gain decrease depends to a large extent on the pump power and the injection current applied to the amplifier. In this way, pump modulation is transferred to the probe with the signal being inverted. Figure 6 shows the principles of cross gain modulation using an SOA.

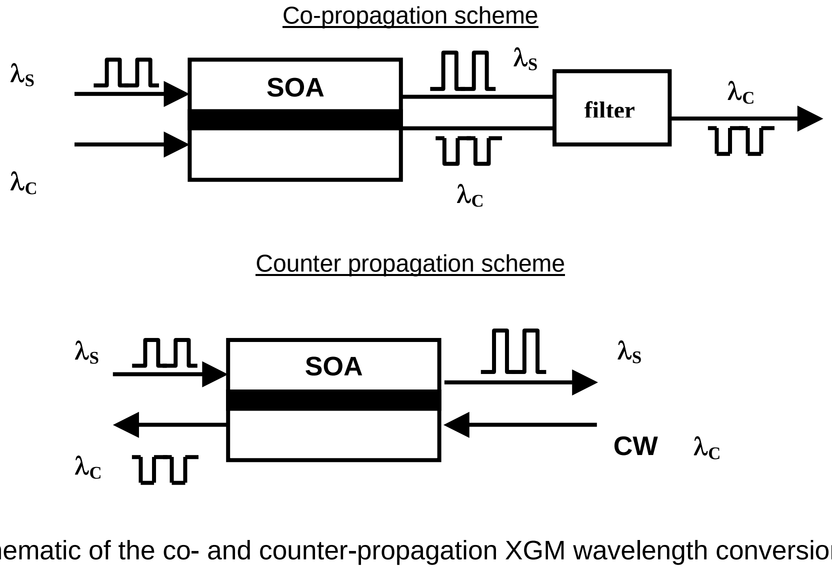


Fig. 6 Schematic of the co- and counter-propagation XGM wavelength conversion principle.

As shown in Fig. 6, the input signal and the CW signal can be launched either in the co- or counter-propagating direction into an SOA. In the latter case an output filter can be avoided and it is also possible to convert the signals to the same wavelength. However, this counter-propagating configuration suffers from a smaller bandwidth as well as an enhanced amplified spontaneous emission (ASE) noise level compared to the co-propagating configuration. The XGM scheme has the advantage of being simple to realize and it can be polarization insensitive if the SOA is polarization insensitive. In order to increase the conversion efficiency for XGM, it is better to reduce the average signal power than to increase the probe power. However, there is a tradeoff between conversion efficiency and output extinction ratio. One major drawback is extinction ratio degradation for up-converted signals.

In summary, the attractions of XGM wavelength conversion devices lie in their simplicity, high conversion efficiency, polarization independence, and their insensitivity to the wavelength of the input data (provided it is within the SOA gain bandwidth). Polarization independence is only ensured if the SOA gain is designed to be polarization independent. The broadband nature of these devices makes them capable of transferring data from one wavelength to several other wavelengths in one device. This may potentially be useful in a wavelength-routed network for broadcast applications.

One disadvantage of devices using XGM for wavelength conversion is extinction ratio degradation. This can be a serious limitation in cascading such devices in an optical network. Another important drawback of XGM wavelength converters is the wavelength chirp induced on the target waveform. This wavelength chirp can severely limit the transmission distance.

Wavelength Converters Based on Cross-Phase Modulation (XPM)

To overcome the problems with extinction ratio degradation with the XGM scheme, the SOA converter can be used in a XPM mode (also called an interferometic mode for wavelength converters based on XPM). The XPM scheme relies on the dependency of the refractive index of the carrier density in the active region of the SOA. An incoming signal that depletes the carrier density will modulate the refractive index and thereby result in phase modulation of a CW signal coupled into the converter. As an example, a structure for a Mach-Zehnder interferometic converter is shown in Fig. 7.

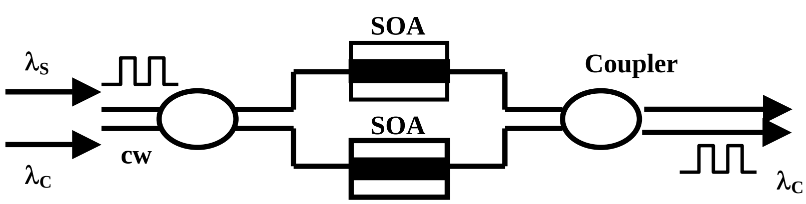


Fig.7 Schematic and principle of operation for interferometic wavelength converters based on XPM in symmetric configuration.

The XPM conversion scheme has the advantage of being very efficient compared to the XGM scheme. It also shows good performance for both up and down converted signals. In such a device the light is split into two paths containing SOAs and a relative phase shift is induced. When the light is recombined, constructive or destructive interference will occur depending on the phase difference between the two paths.

The state of the interferometer is typically set by adjusting the injection current in the two SOAs or by a separate phase tuning element in a passive waveguide. Thus, the first advantage for interferometeric wavelength converters over XGM is the capability to choose between inverting and non-inverting operation.

Additionally, the highly nonlinear behavior can result in reshaping of the incoming data, improvement of the extinction ratio, and redistribution of the noise on the input signal. These properties make this device partially regenerative and thereby increase its cascadability. Furthermore, the chirp characteristic of the wavelength-converted signal can be positive or negative depending on the interferometer bias point. By careful manipulation, the output chirp can be compensated by the dispersion of the fibers and therefore the transmission distance through dispersive fiber can be extended.

In summary, interferometic devices such as Mach-Zehnder interferometers utilizing SOA nonlinearities offer excellent performance in wavelength conversion applications. The main benefits are polarization and wavelength independence, low chirp, noninverting output, partial regeneration of the input, and high extinction ratio. Drawbacks are the restriction to amplitude modulation formats and complex control of the bias point due to the sharp transfer characteristics. Additional drawbacks for monolithically integrated SOA and MZ interferometers are compromises in the SOA design and the complex nature of fabrication.

Wavelength Converters Based on Four-Wave Mixing (FWM)

Four-wave mixing (FWM) is a nonlinear phenomenon that involves optical signals of three different frequencies:
(1) Pump ω_p,
(2) Probe ω_s (=ω_p-$\Delta\omega$),
(3) Conjugates $\omega_p+\Delta\omega$ with $\Delta\omega$ the detuning frequency.

Due to the nonlinear processes in the active layer induced by the pump and the probe beams, a nonlinear susceptibility at the conjugate frequencies is created which generates beams at those frequencies as shown in Fig. 8.

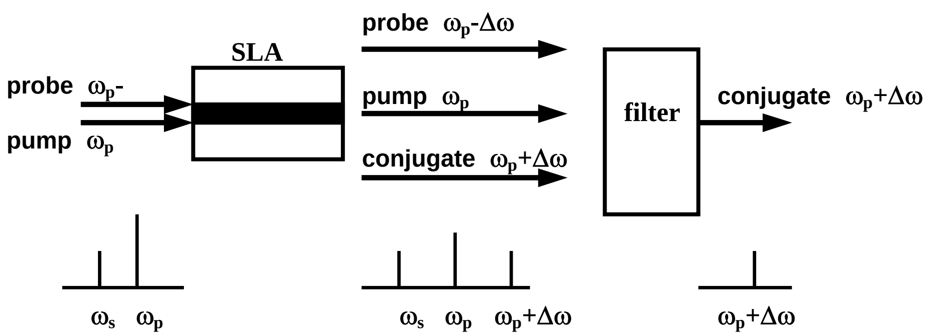


Fig.8 FWM phenomenon in an SOA

FWM wavelength converters offer numerous benefits to the system designer. First, by using a coherent technique they are independent of modulation format. Second, since the wavelength converted signal is the phase conjugate of the input data signal, compensation for fiber chromatic dispersion can be performed. This dispersion compensation technique is known as mid-span spectral inversion. Third, the FWM-based wavelength converters are capable of operation at high speed without compromising extinction ratio.

The efficiency (defined as P_{FWM}/P_{in}) of FWM decreases with the increased detuning because the ultra fast intraband processes that dominate at large detuning are weaker than the interband processes that dominate at small detuning. Furthermore, the interplay between the nonlinear processes within the SOA results in lower efficiency for wavelength up-conversion than for down-conversion. One of the major challenges regarding the utilization of the FWM technique in practical networks is the strong polarization sensitivity of the mixing processes.

In summary, FWM in SOAs has been shown to be a promising method for wavelength conversion. FWM in SOAs is attractive as it is modulation format independent, capable of dispersion compensation, and ultra fast. The main drawbacks are polarization sensitivity and the frequency-shift dependent conversion efficiency.

Summary

Wavelength conversion using SOAs is a rapidly maturing technology with applications in all optical fiber transmission systems. Several approaches exist and each has advantages and disadvantages for the system designer. As yet, there is no single device that can be used in all cases so selection depends on the specific application. Future developments should result in integrated devices with higher functionality and operation at higher speeds.

IV. The Role of SOAs in Advanced Optical Networking

Because of the SOA's amplification and nonlinear characteristics, SOAs or integrated SOAs with other optical components can be used in Long Haul, CWDM, Metro Core and Metro Access networks. The amplifying characteristics of SOAs can boost a laser output to a higher level (power booster), amplify a signal along the transmission line to compensate for loss from attenuation or splitting (in-line amplifier), amplify the signal before the receiver to improve its sensitivity (preamplifier), and perform gain equalization operations on a per-wavelength basis. The nonlinear characteristics of SOAs can be used to perform all optical network functions as discussed in Section I. In the following sub-sections, we will discuss some important applications of SOAs.

The SOA as an Amplifier in Metro Core, Metro Access, and CWDM

The use of SOAs as inline amplifiers has received renewed interest due to the penetration of optical networking into the metro market. An SOA used as a receiver preamplifier is an elegant approach to optical pre-amplification since the SOA can be integrated with the photo detector. An SOA array can even be used as a compact channel equalizer where the wavelength channels can be equalized through gain adjustment on their individual amplifiers. SOAs have already proven their worth in applications for high capacity transmission in metropolitan environments. Therefore, a compact SOA with the potential for mass production and the ability to be integrated into other passive distribution platforms is very attractive for the cost-sensitive metro market.

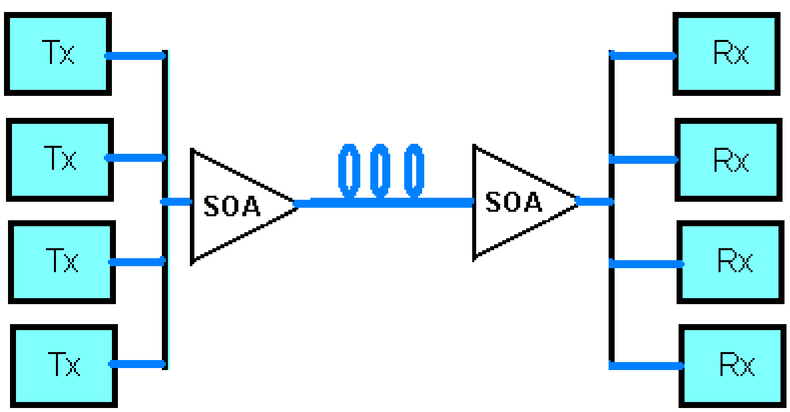
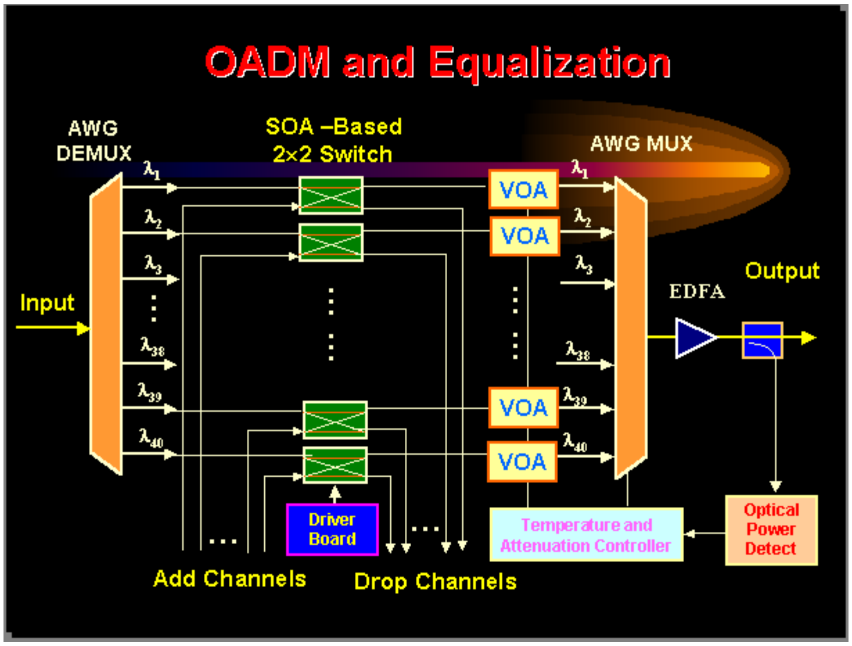


Fig. 9 Application scenarios for SOAs in a 4-channel CWDM system. The SOA can be a booster, pre-amplifier, or a combination of both.

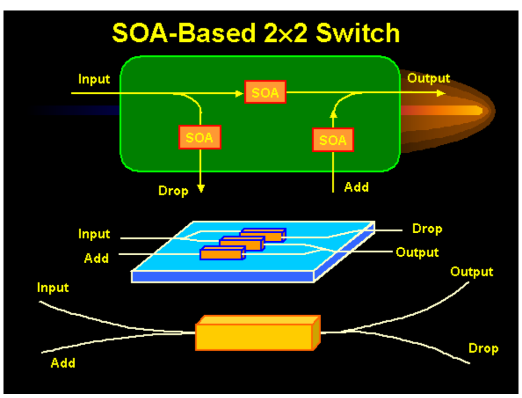
SOAs have a key role in low cost, low channel count amplification and are the only optical amplification technology suitable for CWDM. Fig. 9 summarizes the application scenarios for SOAs in CWDM. The critical parameters of the SOA for CWDM applications are the wider bandwidth, higher saturation output power, and low NF.

SOA as Gates in Long Haul and Metro Core

To overcome electronic bottlenecks in switching and routing, large switching matrices comprised of SOA gates have been constructed to take advantage of the SOA gain to reduce insertion losses. The fast response speed (in the order of hundreds of picoseconds) can be utilized effectively to perform packet switching.



(a)



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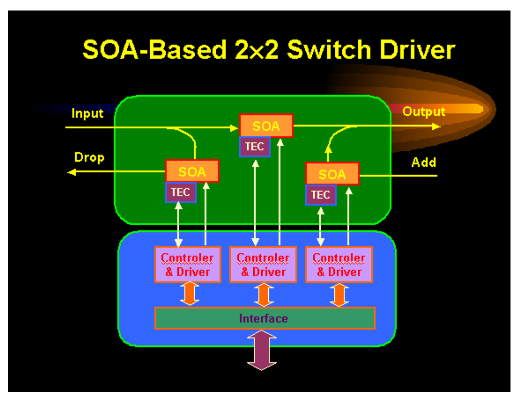

(c)_

Fig. 10 (a) SOA-based ROADM, (b) Three SOA gates are required per wavelength channel, (c) Driver diagram for SOA-based gate switch in ROADM.

Future subsystems need to provide operators in core and metro applications with scalable and flexible networks. One of the key functionalities of these networks is the re-configurable add/drop multiplexer (ROADM). ROADMs extract one or more wavelengths from a fiber (drop) and re-insert different signals on the same wavelength (add). Each of the wavelengths in the multiplex can be reconfigured rapidly to either pass data through or drop it locally and add local data at the wavelength being dropped.

Fig. 10 shows an SOA-based ROADM with up to 40 channels. An AWG is used to distribute and (de) multiplex signals while the SOA gates perform the switching function by changing the drive current. Since each wavelength channel is amplified by individual SOAs, not only is the interchannel crosstalk minimized but also the level of amplification and output power can be adjusted on a per channel basis. The most important characteristics are the degree of isolation between the dropped and locally added channels.

The SOA as an Optical Cross-Connect (OXC) Element

In general, an optical cross connect is no more than a switch fabric providing reconfigurable connections between all inputs and outputs (space switching). Space switching using SOAs is normally done in a broadcast and select configuration where a full connection between input and output ports is realized using adequate power splitters and combiners. Each connecting path can be switched on or off using the corresponding SOAs. More advanced optical cross connect modes can also incorporate wavelength conversion to provide full connectivity (Wavelength-converted switching) with high performance.

The SOA as an All-Optical Wavelength Converter and Regenerator

In section III we have discussed all-optical wavelength conversion using SOAs. From a network performance perspective, devices based on XPM have the better characteristics since they are 2R regenerative, the chirp can be tailored, and the device can operate in inverting and non-inverting data output modes. Using wavelength conversion as a building block, 2R and 3R all-optical regeneration modules can be implemented but 3R regenerative devices based on SOA configurations have so far demonstrated faster performance.

V. Reliability

Like LDs, SOAs are very sensitive to electrostatic discharges, overheating, overdriving by spikes/surges, and negative voltages. External optical feedback should also be avoided or minimized since they may easily result in fatal SOA degradation. SOA reliability and service life also depend on how carefully they are used.

Table. I Telcordia Qualification Test

Test	Sample Size	Specification	Test Status
Mechanical Shock	11	Mil-Std-883, Method 2002	Passed
Vibration	11	Mil-Std-883, Method 2007	Passed
Thermal Shock	11	Mil-Std-883, Method 1011	Passed
Accelerated Aging	50	GR-468-CORE, 5.18	Passed
High Temperature Storage	11	GR-468-CORE, 4.3.2	Passed
Temperature Cycling (un-biased)	11	GR-468-CORE, 5.20	Passed
ESD Threshold	6	GR-468-CORE, 5.22	Passed
Fiber Pull	11	GR-468-CORE, 4.3.2	Passed
Solderability	11	Mil-Std-883, Method 2003	Passed
Flammability	from vendor		
Life time for InP based devices	> 530K hrs		finished
Life time for GaAs based devices	> 10K hrs		In Accel. Aging proc.

Our SOAs have qualified to the Telcordia GR-468 requirements shown in Table. I, which represents significant proof of the reliability of InPhenix SOA products.

VI. Summary

At InPhenix, long term operational stability, reliability, and long life are the key factors considered from design, through manufacturing, to the deliverable SOA device. Our quality control and process monitoring programs have been established to maintain our high manufacturing standards and to provide products that fully satisfy our customers.

Please visit our website for product descriptions and specifications on the wide variety of products available from InPhenix.