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REVIEW OF SEMICONDUCTOR OPTICAL AMPLIFIER (SOA) FUNCTIONALITIES

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Abstract. The Semiconductor Optical Amplifier (SOA) is a photonic device which is increasingly being utilized in many modern state-of-the-art optical communication networks. The SOA provides numerous highly efficient and cost-effective solutions to many network problems, and therefore generates great new interest for a wide variety of applications in future all optical communication systems. SOA based subsystems have been proven to have the capability of implementing the SOA into many practical applications and functions. In this paper, the functionalities of the SOA, based on linear and non-linear responses, are reviewed. The basic applications of SOAs in optical communication systems are also discussed: as post-amplifier (or booster amplifier), in-line amplifier and as preamplifier. In addition, various wavelength conversion schemes based on the inherent nonlinearities of the SOA are reviewed: cross gain modulation (XGM), cross phase modulation (XPM) and four-wave mixing (FWM). Besides wavelength conversion and amplification, SOAs can also be used for future applications such as optical switching, gating and "spectrum-sliced" systems; and these are also reviewed.

Keywords: Semiconductor optical amplifier; amplifications; wavelength conversion; switching; spectrum-sliced

Abstrak. Penguat optik separuh-pengalir (SOA) adalah sebuah peranti optik yang sentiasa meningkat penggunaannya di dalam rangkaian perhubungan optik. SOA yang berdasarkan subsistem telah terbukti kebolehannya dalam pelaksanaan SOA di dalam banyak penggunaan praktikal dan fungsi. Di dalam kertas kerja ini, kefungsian SOA yang berdasarkan sambutan lelurus dan ketidak-lelurusan telah dikaji. Penggunaan asas SOA di dalam sistem perhubungan optik telah dibincangkan: pascapenguat (atau penguat penggalak), penguat sebaris and prapenguat. Selain itu, pelbagai skim penukaran panjang gelombang telah ditinjau berdasarkan SOA ketidak-lelurusan seperti pemodulatan gandaan-silang (XGM), pemodulatan fasa-silang (XPM) dan pencampuran empat-gelombang (FWM). Selain penukaran panjang gelombang dan penguatan, SOA juga boleh digunakan sebagai komponen di dalam pensuisan optik, penggetan dan sistem "hirisan-spektrum". Oleh kerana itu, SOA telah menyediakan pelbagai penyelesaian yang cekap dan kos-berkesan bagi menjanakan kepentingan terkini dalam pelbagai penggunaan sistem perhubungan optik di masa depan.

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Kata kunci: Penguat optik separa-pengalir; amplifications; wavelength conversion; switching; spectrum-sliced

1.0 INTRODUCTION

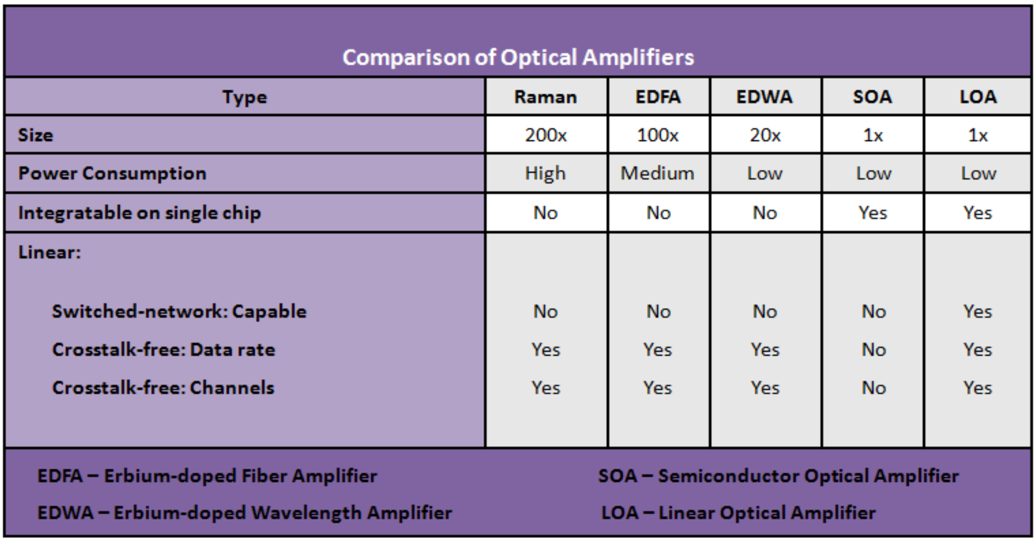
Optical amplifiers play an important role in many evolving telecommunication networks; such as community antenna television (CATV), wavelength division multiplexing (WDM) transmission systems and radio over fibre applications. Besides this, they have also been considered in various space applications, including light detection and ranging (LIDARs) for earth observation and deep space missions, as well as optical inter-satellite communication links (OISL). Therefore, by implementing optical amplifiers together with other optical technologies, they are expected to bring significant improvements towards the overall performance of the networks.

Such applications require efficient optical amplifiers due to the high optical loss throughout a long optical link. An optical link suffers from attenuation and dispersion. Attenuation will cause signal power loss, and hence limit the transmission distance. Meanwhile, the optical pulse will broaden due to the dispersion factor. This, in turn, leads to intersymbol interference, limitation in the fibre bandwidth and also causes an increment in system bit error rate (BER). Therefore, optical amplifiers are required to compensate for these optical losses.

There are many types of optical amplifier technologies which have been developed from recent years to present in order to realize the demanding of growing technologies. Table 1 shows a comparison of optical amplifier technologies. However, SOA can be a more favorable choice when compared with other optical amplifiers due to its various attractive properties.

SOA is an optoelectronic device which is driven by an electrical current (mA) to amplify the input light signal. Motivation for SOA includes their small size and potentials for further integration with other active functions on semiconductor substrate. SOA can be less expensive [1] than EDFA and due to the reduced size, allows them to be integrated easily with semiconductor optoelectronic devices, modulators and other components. SOAs may become a more promising choice of amplifier in the near future by virtue of their intrinsic characteristics such as high gain, low input power requirements, very short response times and multi-functional capabilities [2]. These functions, where there is no conversion of optical signals into the electrical domain, will be required in future transparent optical networks. In addition, SOA with very high gain are available both in the 1300 nm and 1550 nm wavelength regions where attenuation and material dispersion are at a minimal.

Table 1 Performance of optical amplifier technologies [1]



Comparison of Optical Amplifiers

Type	Raman	EDFA	EDWA	SOA	LOA
Size	200x	100x	20x	1x	1x
Power Consumption	High	Medium	Low	Low	Low
Integratable on single chip	No	No	No	Yes	Yes
Linear:					
Switched-network: Capable	No	No	No	No	Yes
Crosstalk-free: Data rate	Yes	Yes	Yes	No	Yes
Crosstalk-free: Channels	Yes	Yes	Yes	No	Yes

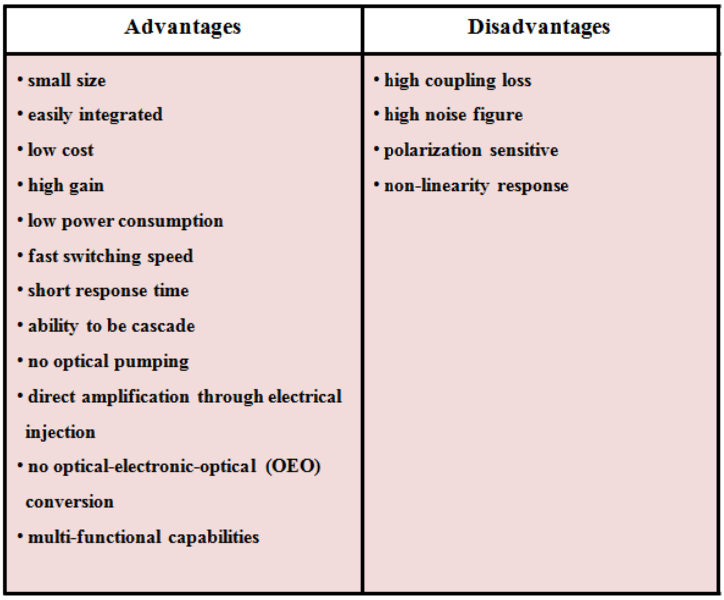
EDFA – Erbium-doped Fiber Amplifier
EDWA – Erbium-doped Wavelength Amplifier
SOA – Semiconductor Optical Amplifier
LOA – Linear Optical Amplifier

Unfortunately, SOA exhibits quite a number of drawbacks. SOA has high coupling loss (around 3 dB) and also high noise figure partly resulting from poor coupling (a typical noise figure is about 7 dB). The most severe problem in optical communications link employing SOA is its nonlinearity, due to a very short lifetime of the injected carriers [3]. SOAs are also slightly polarization sensitive (about 1 dB). As a result, SOA devices will invariably require polarization matching. The polarization of the incident laser must match the polarization of the semiconductor. The interaction between gain and carrier density can be used in a number of sophisticated applications where the SOA serves not only as an amplifier but also as a multi-functional element. Table 2 summaries the advantages and disadvantages of SOA.

2.0 CONVENTIONAL APPLICATIONS

Amplification is a basic principal application of SOAs in optical communication system. SOA is a highly versatile component that can be used for various amplifications and routing functions in telecommunications [4, 5]. Commercialized SOAs are now widely available in the market and are fast becoming a cost-effective solution to optical amplification in advanced optical systems for core, metro, and ultimately access applications. SOA be fundamentally employed in any optical communication network to regenerate signals at various points in the link by operating either as a booster amplifier (post-amplifier), in-line amplifier or as a preamplifier. Figure 1 typically shows the position of these amplifiers in a typical communication system.

Table 2 Advantages and disadvantages of SOA



Advantages	Disadvantages
• small size • easily integrated • low cost • high gain • low power consumption • fast switching speed • short response time • ability to be cascade • no optical pumping • direct amplification through electrical injection • no optical-electronic-optical (OEO) conversion • multi-functional capabilities	• high coupling loss • high noise figure • polarization sensitive • non-linearity response

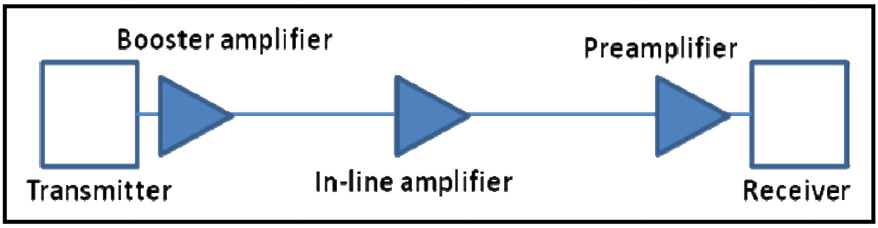


Figure 1 Signal amplification

2.1 Post-amplifier (Booster Amplifier)

The purpose of a booster amplifier which is also known as a post-amplifier in a communication system is to enhance the power of the input signal directly from the light source laser into the transmission link. By employing booster amplifiers, the number of in-line amplifiers required across long spans of fibre in order to avoid signal attenuation is therefore greatly reduced, and subsequently the transmission distance is significantly increased. In addition, booster amplifiers are used in many wavelength division multiplexing (WDM) systems in order to feed the distribution network a strong enough signal before being splitted. For instance, a SOA booster provided a signal gain of 10.8 dB as well as a Q-factor of 8.9 dB for a 2.5 Gb/s signal in selected work [6].

Many papers have been reported on the amplification function employing SOA as a booster amplifier. Tiemeijer et al., [7] presented a packaged MQW booster amplifier for the 1310-nm window, featuring a high 18 dBm saturation output power, two optical isolators to minimize the effects of external reflections, and 17 dB fiber-to-fiber gain. Besides that, a thermoelectric cooler and a thermistor are implemented into the module to control the SOA's temperature. Based on a paper presented by Li et al., [8], saturated SOA can be used as booster amplifiers for dense wavelength division multiplexing (DWDM). However, the fast gain dynamic of saturated SOA introduces severe waveform distortion. Therefore, time-interleaving (TI) scheme was proposed to suppress the inter-channel crosstalk due to both linear crosstalk induced by WDM components and nonlinear crosstalk induced by SOA nonlinearities. A 1 dB gain enhancement was achieved, hence reducing gain suppression of the SOA and increasing the per channel output power for the DWDM signal.

2.2 In-line Amplifier

Amplifiers which are located in a transmission link are called in-line amplifiers. The use of this amplifier is to compensate for fibre losses across long lengths of fibre cable, such that optical regeneration of the signal is considered unnecessary at the end. Advantages of using SOAs as in-line amplifiers include transparency to data rate and modulation format, bi-directionality and high WDM capability [9]. A good example of SOA versatility has been shown in work done by Singh [10] where cascaded in-line SOAs with a span of 70 km has been achieved.

2.3 Pre-amplifier

The use of preamplifier is to increase the power level of an optical signal before detection and demodulation by the receiver. In using a preamplifier, receiver sensitivity is greatly increased and besides, in-line amplifiers which are needed over a distance of fibre cable can therefore be reduced in number. The receiver in optical fibre systems usually consists of some form of optical preamplifier, a narrowband optical filter and a photodiode which is used for detection. The signal from the photodiode is then connected to circuitry used for demodulation. A numerical investigation on the performance of the SOA preamplifier has been presented [11].

3.0 FUNCTIONAL APPLICATIONS

SOAs can be used to perform functions that are, and will be, useful in future optically transparent networks. These all-optical functions can help to overcome the so called 'electronic bottleneck' which is presently a major limiting factor in the deployment of high-speed optical communication networks. Invariably, SOA functional applications are based on SOA nonlinearities. These nonlinearities are principally caused by carrier density changes induced by the amplifier input signals. The four main types of nonlinearity commonly exploited in SOAs are cross-gain modulation (XGM), cross-phase modulation (XPM), self-phase modulation (SPM) and four-wave mixing (FWM).

3.1 Wavelength Converters

SOAs can be used to convert an optical signal to a desired wavelength by either cross-gain modulation (XGM), cross-phase modulation (XPM) or four-wave mixing (FWM) to achieve all-optical cross-connects without opto-electric (OEO) conversion. XPM can also be used to provide 2R (re-amplification, pulse reshaping) or 3R (re-amplification, pulse reshaping and retiming) regenerations.

3.1.1 Cross-gain Modulation (XGM)

Cross-gain modulation (XGM) techniques can be used in wavelength conversion schemes, where a strong input power signal is used to saturate the gain of the SOA and therefore modulates a CW signal carrying the new wavelength. Even though XGM is limited by the relatively slow carrier recovery time within the SOA, impressive wavelength conversions up to 40Gbit/s [11], and with some degradation even up to 100Gbit/s [12], have been demonstrated. XGM-SOA wavelength converter is one of the simplest schemes as compared to XPM and FWM. Furthermore, this scheme yield high conversion efficiency and has larger input power dynamic range. Unfortunately, XGM is accompanied by large chirp and low extinction ratios [13]. Other main disadvantages reported in this process are the polarity inversion of the output data in comparison to the input signal, poor output extinction ratio; high input optical power requirement to saturate the gain of SOA and a bit rate limitation due to the SOA gain recovery time, which can typically vary from 40 ps to 100 ps for different SOAs [14]. Figure 2 shows a XGM-SOA scheme whereby an optical signal at 1540 nm is converter to 1550 nm.

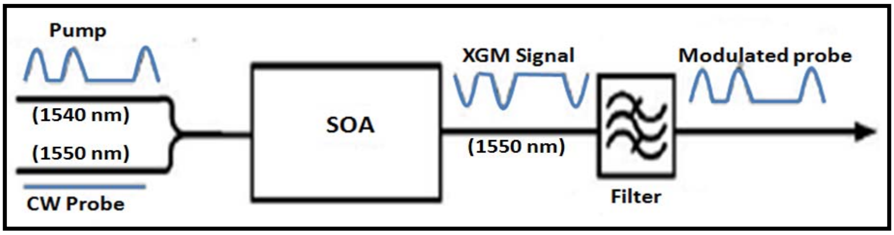


Figure 2 XGM-SOA scheme

3.1.2 *Cross-phase Modulation (XPM)*

The refractive index of the SOA active region is not constant, but is dependent on the carrier density and the material gain. This implies that the phase and gain of an optical wave propagating through the amplifier are coupled via gain saturation [9]. SOA cross-phase modulation (XPM) can be used for wavelength conversion if the SOAs are placed in a Mach-Zehnder (MZI) configuration, as shown in Figure 3 [15]. In Figure 3, the signal at 1570 nm is down converted to 1550 nm. XPM is a non-linear optical effect whereby one wavelength of light can affect the phase of another wavelength of light. Faster SOA-based devices are obtained when using XPM rather than XGM, taking advantage of the steepest part of the SOA nonlinear response curve and thus not being restricted by the carrier recovery [16].

CW light is injected into the MZI at the wavelength of λc and at the output of the converter the light will experience constructive or destructive interference, depending on the phase shift through the SOAs. The SOA phase shift relies on changes in carrier density that can be controlled via the bias current, or the optical input power, which refers to the gain saturation. If optical power is injected into the MZI at a wavelength of λi, the carrier density in the SOA will change due to the increment of stimulated emission. Consequently, the phase and the output power at the wavelength of λc will change [15]. Wavelength conversion is achieved by varying the input power at λi and hence varying the output power at λc.

The advantages of using this scheme are high extinction ratio for both up and down conversion. Besides that, XPM results in low chirping due to the reduced gain modulation and exhibit high conversion efficiency. In addition, it has polarization immunity as well as required low input power to drive the SOA into nonlinearity response.

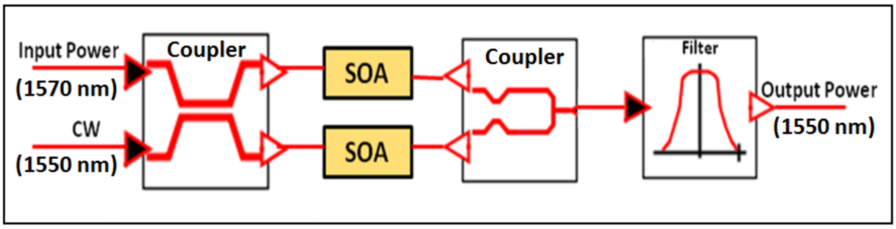


Figure 3 XPM-SOA scheme

3.1.3 Four-wave Mixing (FWM)

A typical scheme of the SOA four-wave mixing (FWM) for wavelength conversion requires a strong pump and a weaker probe signal coupled in, as shown in Figure 4 [17]. The strong pump and the weaker signal waves, at optical frequencies of ω_1 and ω_2 respectively, and with the same state of polarization, are injected into the SOA from the same facet. The beating of the two co-propagating input waves inside the SOA generates refractive index and gain gratings at a frequency, Ω. The input waves are scattered by these gratings which in turn leads to the creation of product waves, the conjugate and the satellite at the optical frequencies of ω_3 and ω_4 respectively.

FWM undoubtedly has the most potential of all the SOA wavelength conversion techniques. It offers transparency, in terms of both bit rate and modulation format, while permitting arbitrary wavelength mapping. FWM also offers very broad conversion bandwidths (up to 70 nm down-conversion) and applied data rates up to tens of gigabits per second (Gb/s) [18]. It generally provides a more attractive way to realize transparent all-optical wavelength conversion. FWM effects can also preserve both phase and amplitude information, whilst the operative SOA is still in possession of its advantageous properties of high nonlinearity, small footprint, high integrity and low power consumption [19]. However, FWM results in polarization sensitive and also exhibit poor conversion efficiency.

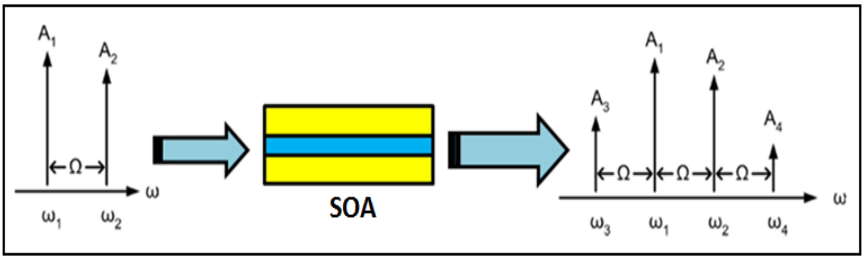


Figure 4 FWM-SOA scheme

3.2 Future Applications

The previously highlighted features of small size, good integration capability and high potential for cost reduction through scaled manufacturing processes will continue to ensure that the SOA plays an increasingly important role in future advanced optical networks. Coarse wavelength division multiplexing (CWDM) is an economic route for giving 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.

There are several other attractive applications of SOA- such as intensity and phase modulator [20], SOA logic for the use of optical signal processing [21], SOA add/drop multiplexer for optical time division multiplexed network [22], SOA pulse generator to generate pulse easily at high frequencies (> 10 GHz) [23], SOA clock recovery required in optical receivers and 3R generators [24], SOA dispersion compensator to overcome the chromatic dispersion which limits the transmission distance [25], and SOA detector to detect optical signal [26].

SOAs can also 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. SOAs may also be employed in “spectrum-sliced” systems of the future, as both noise reducers and functional devices (notably wavelength convertors). Spectrum-slicing techniques, employing incoherent light “bundles” chopped from a common source, have been shown to be a highly practical, economic and therefore very attractive solution for future all-optical networks [6], especially for wavelength-division multiplexing (WDM) transmission systems in local area networks (LAN). In these systems, light is effectively filtered out from broadband ASE sources in “slices” of light. However, the light from such sources possesses very large amounts of intensity noise that greatly limits system performance. A promising approach in reducing this intensity noise can be achieved by utilising the optical nonlinearity properties of a SOA when operated in deep saturation mode. This has been demonstrated in much recent work [27], utilising a saturated SOA introduced into the system as a noise reducer, and is a highly favorable choice due to advantages such as simplicity, high efficiency and potentially low overall cost.

4.0 CONCLUSIONS

The SOA is now believed to be one of the most favorable optical components that can be utilised, when compared with other optical amplifiers, to address many of the required applications that will be necessary within future optical communication systems. The SOA differs from other optical amplifiers in terms of its nonlinearity of response. Although the non-linearity may be viewed as a drawback, it is also proved to be extremely useful in multi-functionality. Both conventional and functional applications can therefore be utilised. The SOA is continuously providing numerous efficient and cost-effective solutions as a tiny optoelectronic device, with tremendous potential for integration with a wide variety of other active and passive optical components. The SOA will therefore continue to generate much new interest for a wide variety of applications in future all-optical communication systems, and may well become the choice device to use.

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