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A Technical Review on Semiconductor Optical Amplifiers (SOAs) and their Applications

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Abstract In last few decades, a major revolution has taken place on the electronic system and in the optical communication networks. The implementation of semiconductors to enhance optical signal was invented many years ago. The Semiconductor Optical Amplifiers (SOA) have much viability in different application areas. Nowadays, SOAs have been considered as one of the key solutions to for number functionalities in the evolution of electronic as well as communication systems. The requirement of moving towards the ultra-wideband systems and many other applications has enabled the usage of semiconductor optical amplifiers. This review paper focuses to describe some of the basic concepts behind the semiconductor optical amplifiers including the static and dynamic parameters characterizations. This survey paper also describes the various ranges of crucial applications of SOAs in several fields (such as: in packet switching, in UWB systems, in OCDMA systems etc.)

Keywords: *SOA, Static and dynamic parameters, packet switching, UWB, OCDMA*

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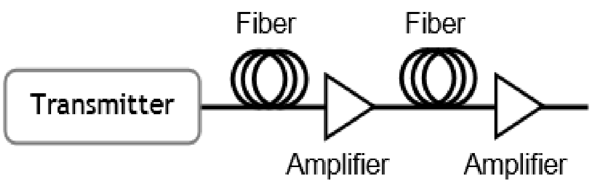
1. Introduction

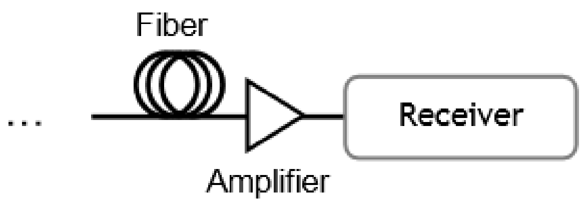
Amplifiers are responsible for power enhancement of an electrical circuit or system. Similarly, semiconductor optical amplifiers play the role in amplifying optical signals and these are based on the principle of semiconductor gain. Today, the advancement, demand and implementation of fiber optics communication system are in a state of rapid growth. Nowadays, optical communication/ fiber optic communication systems aim for transmitting data rates up to several Tb/ s. Therefore, an advance system needs some advanced components and today, optical amplifiers are considered as one of the exciting area of research and implementation.

Optical amplifiers are in general divided into two categories. Such as Semiconductor Optical Amplifier and Optical Fiber Amplifier [1]. This review paper aims to discuss in detail about the semiconductor optical amplifiers (SOA). In [2], the authors have mentioned that, a long haul fiber optic transmission system needs optical amplifiers for the regeneration of signal with amplification. Semiconductor Optical Amplifiers (SOAs) are low power consumption, small sized and uncomplicated device that best suit for optical amplification. Noise affects the SOAs in the long haul communication system however; they are the best choice for optical wavelength conversions.

Semiconductor Optical amplifiers are made up of group III-V compound semiconductor crystals [3]. The below Figure 1 shows an ideal optical transmission system.



(a)



(b)

Figure 1. Schematic of Optical Transmission system (a) Transmitter, (b) Receiver [3]

This review paper will be discussing the basic structure, equation & operation of the Semiconductor Optical Amplifiers. Apart from the same, the range of applications in Networking, Ultra-wideband system, Optical packet switching and managing chirp of OCDMA will be discussed thoroughly in the subsequent sections of this review paper.

2. Stricture of Semoconductor Optical Amplifer

The basic structure of a Semiconductor Optical Amplifier contains the following elements such as input facet, Active region (also called as intrinsic region), Waveguide, Output facet as shown in the below Figure 2.When input signal (current) is applied at the input facet, the output signal is accompanied with an additive noise and the additive noise is called as amplified spontaneous emission. As shown in the figure below, the input signal flows into the intrinsic region that is responsible for creating huge numbers of holes and electrons. The intrinsic region can also be considered as the active region. The amplified spontaneous emission is caused during the amplification process [1]. The internal noise generated during the amplification process and the input signal affects the gain of the semiconductor optical amplifiers. The schematic of the Semiconductor Optical Amplifier is shown below.

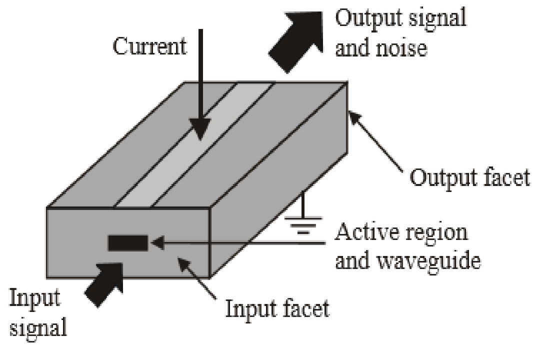


Figure 2. Schematic of Semiconductor Optical Amplifier [1]

It is observed that, the gain of the SOAs decreased when there is a drastic increase in the input signal power. A typical graphical representation of the SOA gain saturation is shown in the below Figure 3.

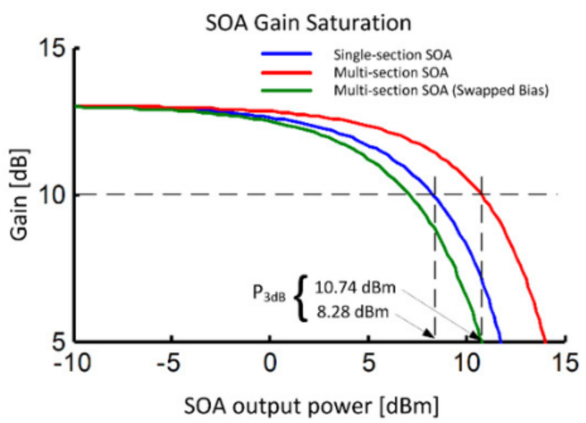


Figure 3. Gain Saturation of the Semiconductor Optical Amplifiers [4]

Semiconductor Optical Amplifiers are generally made up of InGaAsP/InP. An investigation of the energy bands of the semiconductor provides a proper analysis to the associated optical properties of the semiconductor optical amplifiers [3,5]. In the next session, the characterization of some of the static parameters of SOA has been explained.

3. Static Parameter Characterization of SOA

Noise figure, saturation power and gain are considered as the static parameters of Semiconductor Optical Amplifiers. The below figure shows the experimental setup for characterizing the static power [3]. The static parameters must be characterized to model the semiconductor optical amplifier (SOA).

The experimental setup consists of the following components such as DFB laser, Multiplexer, Variable optical attenuator (VOA), SOA, Optical spectrum analyzer and switch. In this setup the Distributed Feedback lasers (DFB) lasers are responsible for generating continuous wave then the multiplexer multiplexes the selected optical channels. In [3], it is explained that, the job of Variable optical attenuator is to control the input power (multiplexed signals) that enters the semiconductor optical amplifier as shown in the above Figure 4. The output of the SOA is connected to the optical switch then the switch is connected to the optical switch analyzer.

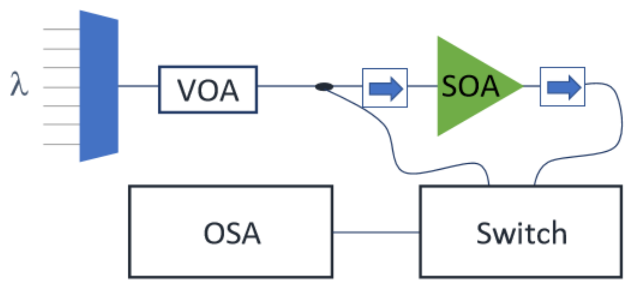


Figure 4. Experimental setup for characterising static parameters [3]

In order to measure the noise figure, the input power, OSNR Output, and $OSNR_{input}$ should be measured. However, there is a need of selecting low input power to successfully determine the difference between the output and input SNR respectively [3]. The $OSNR_{output}$ is responsible for estimating the accuracy.

4. Relative Intensity Noise (RIN) Response (Dynamic Parameters Charactarization)

This section of the review paper aims to discuss a bit about the characterization of the dynamic parameter i.e. relative intensity noise (RIN). The formula for relative intensity noise is given below. The relative intensity noise is defined as the ratio of the spectral density of noise power to the total power as represented in the below formula [6].

$$RIN = \frac{Noise\ Power\ Spectral\ Density}{Total\ Power} \qquad (1)$$

The below experimental setup explains more about the same.

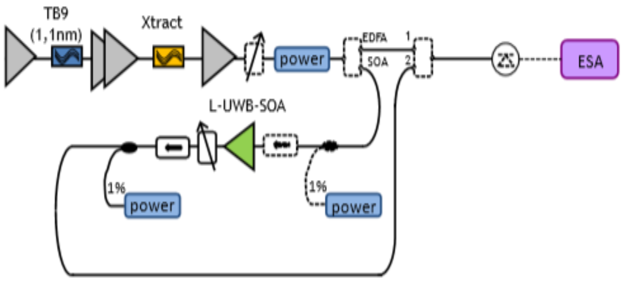


Figure 5. Experimental setup for characterising Relative Noise Intensity [3]

The setup as shown above consists of two optical switches, which measures the input signals and output signals of the semiconductor optical amplifier [3]. In this setup, a photodiode is used to detect the optical signal and convert the same to electrical domain and at the end, the electrical spectrum analyzer as shown above [3] is analyzing the electrical signal. In [3], the authors mentioned that, the relative intensity noise response is achieved by subtracting the frequency response of the injected input signal from the signal generated from semiconductor optical amplifier (SOA). The subsequent sections of this review report aims to focus on various ranges of applications of the semiconductor optical amplifiers in various fields.

5. Range of Applications of Semiconductor Optical Amplifiers (SOA)

This section aims to provide information about various ranges of applications of the semiconductor optical amplifiers in various fields. The subsequent subsections of this section will cover up the application areas of SOAs in packet switching, UWB systems, and applications in managing chirp of OCDMA, SOA as booster and pre-amplifiers, and applications in NRZ to RZ optical conversion.

A. Semiconductor Optical Amplifiers (SOAs) Applications in Packet Switching

The growing demand for network usage and their capacity lead to an adoption of optical network supporting packet transmission and routing [8]. The Semiconductor optical amplifier has been considered as one of the promising candidate to achieve the following functionalities such as wavelength conversion, power equalisation, gating and routing etc [7]. The authors of [7] have explained about some of the improvements such as control of optical mode profile, increased output power, Integration with waveguides, optical network switching optimisation and gain clamping etc of the Semiconductor Optical Amplifier (SOA). Apart from this, the authors have also briefed about some of the traditional SOA applications (such as SOA as power booster, pre-amplifier etc.). This section is dedicated discuss about the following SOA applications in packet switching such as High-speed gating, Optical wavelength conversion, optical logic, regeneration, power equalization and control.

Semiconductor optical amplifiers can act as a gate in which the signals will be routed through it. An unbiased SOA strongly absorbs and consequently blocks the signals attempting to pass through the same [7]. So, in this way, SOAs can be implemented in the high speed gating. Secondly, in [9], the authors have explained that, the probability of port blocking is being increased as well as the connection path probability is getting limited due to the inability of switching data packets between the optical carriers. The all-optical wavelength convertors (AOWC) play a vital role in the present day optical infrastructures. The AOWCs allows not sending the data back to the electrical domain before they are relaunched to the desired wavelength [7]. The AOWCs follows three important conversion mechanisms such as cross gain modulation, cross phase modulation and four wave mixing. The authors of [10] explain that, the cross gain modulation format considers the gain properties (saturated) of the semiconductor optical amplifier to print the inverted category of the actual signal onto the continuous wave signal. The cross gain modulation formats are robust in nature. The semiconductor optical amplifiers (SOAs) are placed in the interferometer configuration by the cross phase modulation formats as shown in the below figure [7]. Placing SOAs in interferometer configuration leads to consider the phase of the modulated signal that go along with the gain saturation that further modulates the continuous wave signals generated by the lasers.

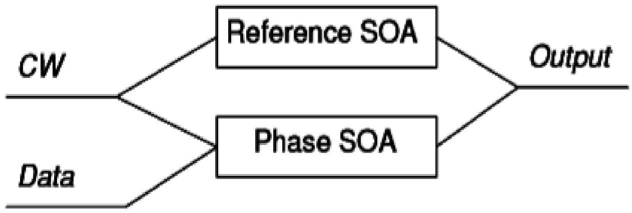


Figure 6. A typical cross phase modulator with AOWC [7]

In AWOCs, the four-wave mixing conversion mechanism shows good performance up to almost 80 GB/s [7,11].

The authors of [7] have mentioned that, the regeneration technique is needed for the long haul transmission line or communication systems and the cross-phase modulation formats have a unique attribute called non-liner transfer characteristics. The non-liner transfer characteristics are responsible for regenerating optical signals in the long haul communication link [12].Semiconductor optical amplifiers have applications in optical logic as well. SOAs are being used in multiple applications in a flexible optical layer [7]. Apart from optical logic, the semiconductor optical amplifiers direct control can be utilized to enable high-speed power equalization [13].

B. SOA for Ultra-Wideband (UWB) System

This section is dedicated to provide the application of semiconductor optical amplifiers in the ultra-wideband systems. Initially, the usage of semiconductor optical amplifiers was very limited to passive optical networks [14]. As we know, in optical transmission system, EDFAs have been widely used however; EDFAs are not capable to provide a wider bandwidth. Therefore, in this case semiconductor optical amplifiers are considered as one of the best solutions for achieving wider bandwidth [3]. In UWB system, the implementation of SOA has been considered as one of the novel approaches. In this system, the semiconductor optical amplifiers are used to amplify a single light polarization [3]. Therefore, in this way the polarization diversity is being exploited by using SOAs. The below figure describes the way semiconductor optical amplifiers are using the polarization diversity strategy.

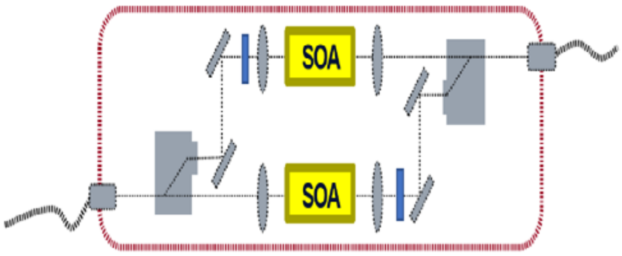


Figure 7. A typical cross phase modulator with AOWC [3]

In the above figure, light signals are entering the cavity and splitting into two parts by the polarization beam splitter [3] and it can be seen that each signal is being amplified by using a single semiconductor optical amplifier. At the end, the two signals are finally recombined at the output of the semiconductor optical amplifier (SOA) [3].

The chip designing part of the semiconductor optical amplifiers in the UWB systems plays an important and challenging role in the industries as well. Some of the key factors/ elements such as nonlinearities of the fiber optic cable and optical signal to noise ratio should be taken into account in a particular optical long haul transmission system. The authors of [3] have described that, the UWB amplifiers require two most important factors i.e. high power and gain. The authors of [15] have constructed a UWB module with more than one quantum well by using InGaAsP in the III-V labs and as a result, the bandwidth of the SOA increased dramatically. The advantage of the UWB module is that, the semiconductor optical amplifier even operates in a high power due to the increase in the saturation power [3]. Therefore, in this way the semiconductor optical amplifiers can play an important role in the design of UWB chip and system as well. The next subsection of this survey aims to brief about the applications of SOA in Managing Chirp of OCDMA systems.

C. SOA Applications in Managing Chirp of OCDMA

The flow of ultra-high data rates in optical fiber communication can also be affected severely by chromatic dispersion. The authors of [16] have mentioned that, a tiny deviation in the optical transmission link associated with dispersion compensated optical fiber can strongly affects the performance of the optical code division multiple access (OCDMA) systems. Then the implementation of the semiconductor optical amplifiers (SOA) appears in the picture. The authors [16] suggested that, the semiconductor optical amplifiers could be employed in the optical transmission system to control over the chirp of the optical signals to exploit SOA ability for dispersion management and the authors have also used the semiconductor optical amplifiers for the at the transmitter side of the OCDMA system to eliminate the negative effects of temperature fluctuations of the optical fiber. The experimental setup is shown in the below Figure 8.

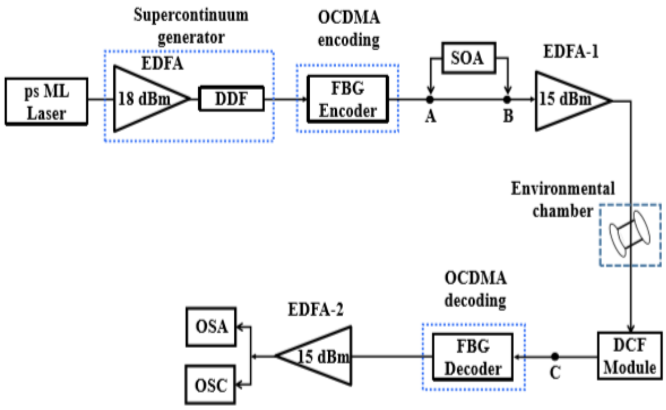


Figure 8. A typical cross phase modulator with AOWC [16]

In the above experimental setup the SOA is used at the transmitter side to control the chirp of the OCDMA carriers prior to transmitting the optical transmitting link as shown in the figure. In the above experimental setup the semiconductor optical amplifiers are responsible for eliminating the fiber temperature [16].

D. SOA applications as Booster Amplifier and Pre-amplifier in Optical Transmission Channle

The applications of the semiconductor optical amplifiers (SOA) in the optical communication system as boost amplifier and pre-amplifier falls under the basic networking applications. The booster amplifier is implemented in the transmitter side and the preamplifier is implemented at the receiver side prior to the photodiode in an ideal optical communication systems. The location of the booster amplifier and pre-amplifier is shown pictorially blow.

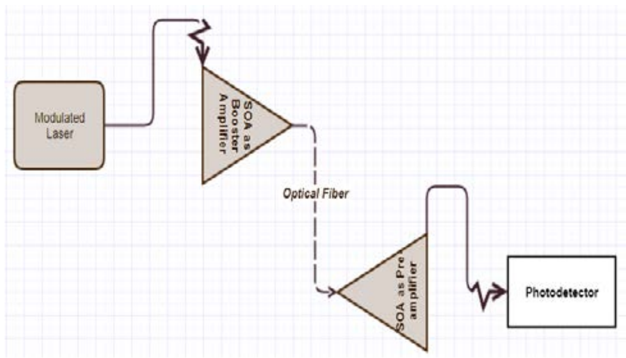


Figure 9. Schematic SOA Applications as Booster and pre-amplifier. Inspired from [1]

As shown in the above figure, the modulated laser (transmitter) signal passes to the SOA as pre-amplifier prior to transmission over the optical channel. The prime aim of introducing a booster amplifier at the transmitting aim is to enhance the optical signal generated from the optical modulator as shown in the above picture. The author [1] have mentioned that, the application of SOA as booster amplifier can significantly reduce the number of optical regenerators in the optical channel which results in the reduction of cost.

Pre-amplification is needed for very high optical gain and low noise operations in an optical transmission system. The authors of [17] have mentioned that, the SOA pre-amplifier applications are in the metro systems and combination of WDM filter with the SOA pre-amplifier produces a cost effective solution for the WDM receiver. SOAs are used as pre-amplifiers to enhance the power level of the optical signals. A typical pre-amplified optical receiver is show in the below Figure 9.

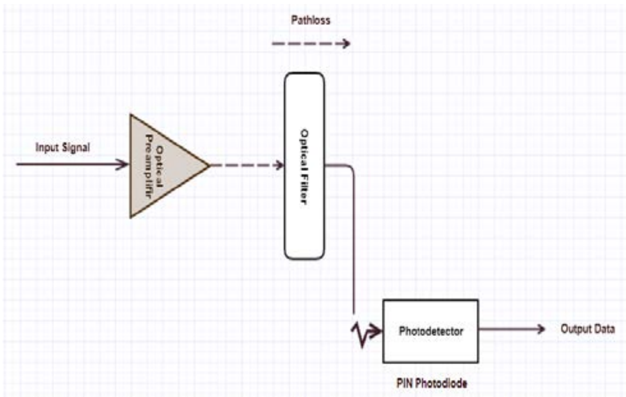


Figure 10. Schemtic for SOA as Pre-amplifier Optical Receiver. Inspired from [1]

The sensitivity of the receiver could be improved by enhancing the power level.

E. SOA Applications in Optical NRZ to RZ Conversions

Semiconductor Optical Amplifiers have major applications in the field of digital electronic systems. SOAs has been employed in the optical communication networks to perform some important signal processing functions such as regeneration, logic gates and wavelength conversion [18]. Optical data format conversion is one of the useful functions between Non-return zero and return zero. SOAs are employed in the signal processing operations during RZ conversion. The authors of [18] have presented a SOA based 42.6 Gbps optical NRZ to RZ convertor using the modulation formats cross phase modulation. The below Figure 11 shows the experimental setup for the same.

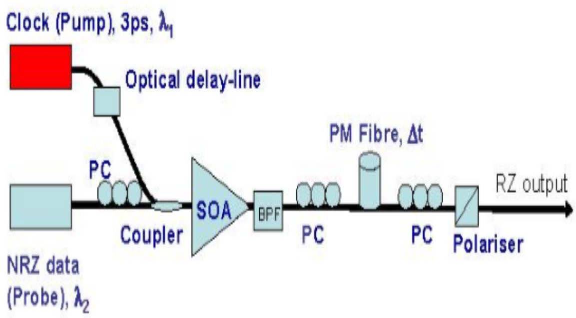


Figure 11. Schematic for NRZ to RZ conversion [18]

It can be seen from the above figure that, the SOA is receiving an input data beam from the NRZ data probe and clock pulses are generated from the pump that introduces periodic phase shifts in SOA. Therefore, in this way the SOAs can be employed in the optical networks for NRZ to RZ conversions.

6. Conclusion

Semiconductor Optical Amplifiers have been a pioneer solution to many applications in the electronic systems and as well as to the communication systems nowadays. Initially, this review paper briefed about the optical transmission systems. This review paper talked about the structure of the semiconductor optical amplifiers and gain saturation. This paper also described about some of the static and dynamic parameters of SOAs. This paper also covered the application areas of SOAs in packet switching, UWB systems, and applications in managing chirp of OCDMA, SOA as booster and pre-amplifiers, and applications in NRZ to RZ optical converters. In SOA packet switching applications, the authors have explained about the implementation of semiconductor optical amplifiers as the regenerators in the long haul transmission line. In ultra-wideband systems, the polarization diversity is being exploited by using SOAs. Therefore, in this case SOA has been considered as one of the potential solutions. In this paper, the application and implementation of SOA in the OCDMA systems have been explained. The semiconductor optical amplifiers are used at the transmitter side of the OCDMA system to eliminate the negative effects of temperature fluctuations of the optical fiber. Semiconductor optical amplifiers could be employed in the optical transmission system to control over the chirp of the optical signals to exploit SOA ability for dispersion management. This survey paper provides information about the applications of semiconductor optical amplifiers as booster and pre-amplifiers in the optical communication systems. The main advantage of using SOAs as booster and pre-amplifier is to reducing the usage of number of regenerators in the optical transmission line. The prime aim of introducing a booster amplifier at the transmitting aim is to enhance the optical signal generated from the optical modulator. Finally, the last part of the review paper describes about the application of SOAs in the optical NRZ to RZ conversions.

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