Semiconductor optical amplifiers in optical Communication system-Review

Aruna Rani [1], Mr. Sanjeev Dewra [2]

[1]M.tech Scholar, Shaheed Bhagat Singh state technical campus, Ferozepur.

[2]Assistant professor & Head of ECE Department, Shaheed Bhagat Singh state technical campus, Ferozepur.

Abstract

In this paper Semiconductor optical amplifier and their applications have been reviewed. SOAs are under rapid development to achieve polarization independent gain, low facet reflectivity, good coupling to optical fibers, and high saturation power. A single optical amplifier can replace all the multiple components required for an electronic regeneration station and eliminate the need for electrical-optical and optical-electrical conversions. SOAs have been employed to overcome distribution losses in the optical communication applications and pursued for metropolitan-area networks as a low-cost alternative to fiber amplifiers**.**

Keywords – Optical communication system**,** Semiconductor optical amplifier, Wavelength converter, Fabry-Perot Semiconductor Optical Amplifier

1. Introduction

As the optical signal travels in a fiber waveguide, it suffers attenuation (loss of power). For very long fiber spans, the optical signal may be so attenuated that it become too weak to excite reliably the (receiving) photo detector, where upon the signal may be detected at an expected low bit error rate ($\sim10^{-9}$ to $\sim10^{-11}$)[1].Optical amplifiers are key devices that reconstitute the attenuated optical signal, thus expanding the effective fiber span between the data source and destination. A semiconductor optical amplifier is an optical amplifier based on a semiconductor gain medium. It is essentially like a laser diode where the end mirrors have been replaced with anti-reflection coatings. Optical amplifiers amplify incident light through stimulated emission, the same mechanism that is used by lasers. An optical amplifier is nothing but a laser diode without feedback [2].Indeed, the history of optical amplifiers is as old as that of lasers, the only significant difference being in the presence or absence of feedback elements such as end mirrors or gratings [3]. Optical amplifier can amplify all WDM channels together, and is generally transparent to the number of channels, their bit-rate, protocol, and modulation format. Optical amplifiers require electrical or optical energy to excite (pump up) the state of electron hole pairs. Energy is typically provided by injecting electrical current (in SOA) or optical light in the UV range (in EDFA).To reduce optical signal losses at the couplings, antireflective (AR) coatings are used at the optical fiber-device interface as shown in Fig.1

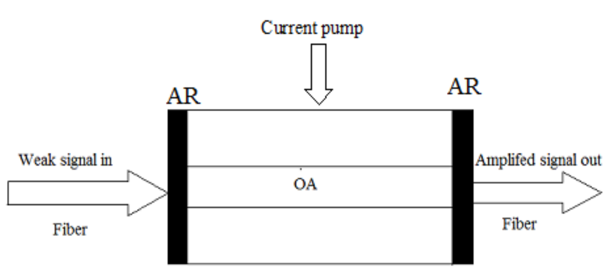

Figure 1 Optical amplifier based on laser principle

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. Semiconductor optical fiber amplifier operates in both the 1300-1550nm transparent window but EDFA operates only in 1500nm window.

2. Applications of Semiconductor optical Amplifiers

In terms of the functionality Semiconductor optical amplifier is categorized into three areas: (a) Post amplifiers or Booster to raises the power of an optical signal to the highest level, (b) in line amplifiers to compensate for fiber and other transmission losses in medium and long haul links and (c) pre amplifiers to improve receiver sensitivity and high gain.(d) Wavelength converter [4].

1)Post amplifier or booster: It is a power amplifier that magnifies a transmitter signal before sending it down a fiber as shown in Fig.2. A Booster raises the power of an optical signal to the highest level which maximizes the transmission distance. A power amplifier can increase the transmission distance by 100 km or more depending on the amplifier gain and fiber losses. The main requirement of this amplifier is to produce maximum output power not maximum gain because the input signal is relatively large; it comes immediately from a transmitter.

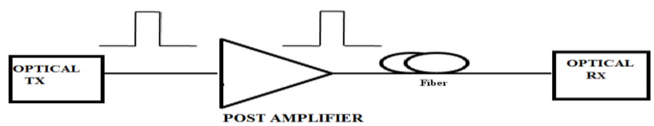

Figure 2 Semiconductor Optical Amplifier as Post Amplifier

Booster amplifiers are also needed when it is required to simultaneously amplify a number of input signals at different wavelengths, as is the case in WDM transmission.

2**) In-Line amplifier:** In-line optical amplifiers operate with a signal in the middle of a fiber optic link as shown in Fig.3. The function of this amplifier is to compensate for fiber loss across lengths of fiber cable caused by the fiber attenuation, connections, and signal distribution in a network, such that optical regeneration of the signal is unnecessary.

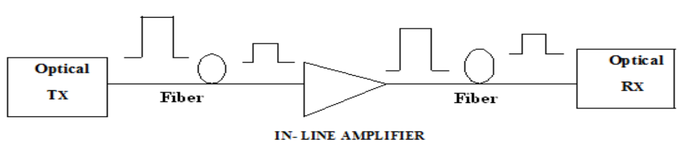

Figure 3 Semiconductor Optical Amplifier as In-Line Amplifier

3) Preamplifier: The use of SOAs as a preamplifier is attractive: it permits monolithic integration of the SOA with the receiver. Preamplifier amplifies a signal immediately before it reaches the receiver as shown in Fig.4. By using a preamplifier, the sensitivity of the receiver can be greatly increased. Similar to the use of booster amplifiers, pre-amplification can reduce the number of in-line amplifier needed over a distance of fiber.

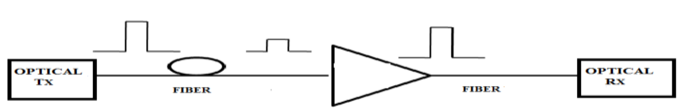

Figure 4 Semiconductor Optical Amplifier as Preamplifier

4) Wavelength converter: Wavelength converters will play an important role in optical networks. A wavelength converter is an optical device which is used for converting an injected signal of light from one wavelength to the desired wavelength in a system or network [5]. Optical wavelength converter will be used to avoid wavelength blocking in cross-connects in WDM systems. There are three primary ways of exploiting the non-linear properties of SOAs for wavelength conversion: cross gain modulation (XGM),cross phase modulation (XPM) and four wave mixing (FWM). SOA based wavelength converters have employed intraband Four wave mixing, requiring relatively high pump powers [6].The principle behind using a SOA in cross gain modulation mode is shown in Fig.5. A continuous wave signal (CW) at the desired output wavelength (λ_c) is modulated by the gain variations so that it carries the same information as the original input signal.The XGM scheme gives a wavelength converted signal that is inverted compared to the input signal.The operation of a wavelength converter using SOA in cross gain modulation mode is based on the fact that the refractive index of SOA is dependent on the carrier density in its active region.An incoming signal that depletes the carrier density will modulate the refractive index and thereby result in phase modulation of a CW signal (wavelength (λ_c).

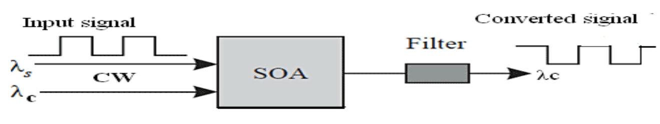

Figure 5 Wavelength converter based on XGM in SOA

Where, λ_s is the input signal wavelength, λ_c is the converted wavelength. Wavelength conversion technique based on FWM in the SOA has high bit rate capability and transparency to modulation format[7].

3. Design of Semiconductor Optical Amplifier

Semiconductor optical amplifiers (SOAs) are essentially laser diodes, without end mirrors, which have fiber attached to both ends. SOAs amplify incident light by the stimulated emission process using the same mechanism as laser diode. An optical input signal enters the semiconductor active region through coupling optics as shown in Fig.6. Coupling is required because the MFD of a single mode fiber is typically 9.3µm.Injection current delivers the external energy necessary to pump electrons at the conduction band. The input signal stimulates the transition of electrons down to the valence band and emission of photons with the same energy that is the same wavelength that the input signal has. Thus the output is an amplified optical signal [8].

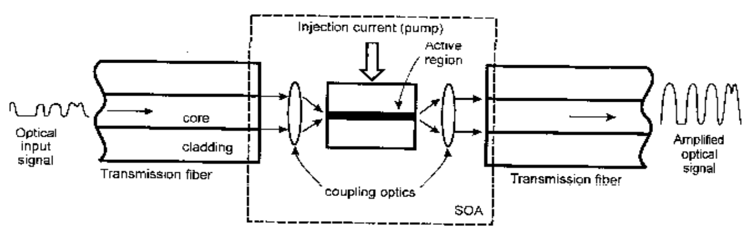

Figure 6 Semiconductor Optical Amplifier

The semiconductor optical amplifiers (SOAs) has wide gain spectrum, low power consumption, ease of integration with other devices and low cost. Therefore, this amplifier increases the link distance which is limited by fiber loss in an optical communication system [9]. Semiconductor optical amplifier can easily be integrated as preamplifiers at the receiver end use same technology as diode laser, gain relatively independent of wavelength. The large signal amplification gain of SOA is obtained:

$$G = \frac{Pout}{Pin} \qquad (1)$$

At low value of bias current for SOA, the amplification factor (G) decreases with increase in input power even amplified spontaneous emission noise power, noise figure & total noise is quit low. These leads to increase in inter channel crosstalk in a multi-channel transmission system [10]. When SOA is used as single-channel transmission, the small signal gain g_0 is given:

$$g_0 = (\Gamma\alpha/v)(N-N_t) \quad \text{———} \quad (2)$$

Where (Γ is the confinement factor, α is the differential gain, v is the active volume, N is carrier population is N_t is the transparency carrier density.

When SOA is used to amplify several channels simultaneously, non-linear phenomenon such as cross gain saturation, inter channel crosstalk & four wave mixing induced. These non-linear phenomenons originate from stimulated recombination term given by [2].

$$\frac{\partial N}{\partial t} = \frac{1}{q} - \frac{N}{\tau_c} - \frac{\alpha(N-N_t)}{\sigma_m \, \mathrm{hv}} P \quad \text{———} \quad (3)$$

Where N is carrier population, τ_c is carrier lifetime, q is charge of electron, α is differential gain, N_t is the transparency carrier density, σ_m is cross-sectional area of the waveguide mode, v is the active volume. When multiple channels are amplified, the power, P is obtained: [2].

$$P = \frac{1}{2} \left| \sum_{k=1}^{N} A_k \, \exp(-iw_k t) + cc \right|^2 \quad \text{———} \quad (4)$$

Where, N is the no. of channels, A_k is the amplitude, w_k is the carrier frequency of the k^{th} channel and cc is complex conjugate. The gain of specific channel is saturate not only by its own power but also by the power of neighboring channels; this phenomenon is cross–gain saturation. A source of inter channel crosstalk is cross gain saturation occurring because the gain of a specific channel is saturated not only by its own power (self saturation) but also by the power of neighboring channels. The inter channel crosstalk that cripples SOAs because of the carrier density modulation. This mechanism of crosstalk can be avoided by operating the amplifier in the unsaturated regime. The parameters used in the semiconductor optical amplifier with their typical values are shown in table1.[11].

Table 1. Parameters used in Semiconductor optical amplifier

Symbol	Parameter	Typical value
I	Bias current [mA]	100
L	Amplifier Length [μm]	300
W	Active Layer Width[μm]	1.5
d	Active Layer Thickness[μm]	0.15
Γ	Confinement Factor	0.35
N_0	Transparency carrier density [cm^{-3}]	10^{18}
A	Material gain Constant [cm^2]	$3\text{x}10^{-16}$
α	Line width Enhancement Factor [cm^{-1}]	3
α_P	Material Loss[cm^{-1}]	10.5
α_{int}	Input/output insertion loss [dB]	3
P_s	Saturation Power[mw]	21.36

4. Types of Semiconductor Optical Amplifiers

1)Fabry-Perot Semiconductor Optical Amplifier (FPSOA):

The Fabry-Perot Semiconductor Optical Amplifier is same as the Fabry- Perot laser. A laser's two end surfaces are cleaved to make them works as mirrors as shown in Fig 7. The Light entering the active region is reflected many times from cleaved facets and having been amplified. When the light enters FPA it gets amplified as it reflects back and forth between the mirrors until emitted at a higher intensity. It is sensitive to temperature and input optical frequency. Using a Fabry-Perot resonator, which provides optical feedback, can increase the gain of SOA. FPA has very high gain within a narrow bandwidth. In other words, FP SOA is a laser diode where gain is less than loss. The amplification factor of FP SOA is given by

$$\Delta v_A = \frac{2\Delta v_L}{\pi} \sin^{-1} \frac{1-G\sqrt{R1R2}}{(4G\sqrt{R1R2})^{1/2}} \qquad (5)$$

where, Δv_L is free spectral range of FP cavity. The amplifier bandwidth is a small fraction of the free spectral range of the FP cavity (typically $\Delta v_L \sim 100$ GHz and $\Delta v_A < 10$ GHz). Such a small bandwidth makes FP amplifiers unsuitable for most light wave system applications.

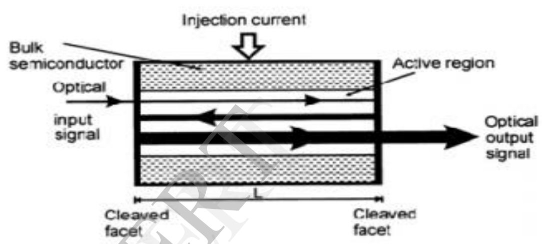

Figure 7 Fabry-perot semiconductor optical amplifier

2)Traveling wave Semiconductor Optical Amplifier (TWSOA):

To create a traveling wave SOA, the resonance in the Fabry-Perot cavity must be suppressed. Reflectivity must be extremely small (<0.1%) for the SOA to act as TW amplifier. Three special approaches are used to reduce the reflectivity of these mirrors: with an antireflection coating, tilting the active region with respect to facets and using buffer material between the active region and the facets (using transparent window). Traveling wave amplifier is an active medium without reflective facets so that input signal is amplified by a single passage through the active medium as shown in Fig 8. Since the gain of TWA can be increased by extending the length of the active medium[8]. Reflectance should be zero in Traveling wave Semiconductor Optical Amplifier. They widely used because they have a large optical bandwidth, and low polarization sensitivity.

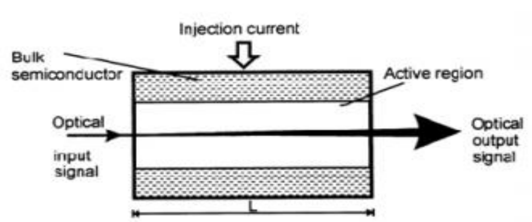

Figure 8 Traveling wave Semiconductor Optical Amplifier

3)Vertical-Cavity Semiconductor Optical Amplifiers (VCSOA):

The vertical-cavity semiconductor optical amplifier (VCSOA), as a specialized form of the FPSOA, has existed for several years now [12]. A VCSOA can be simply described as a vertical cavity surface emitting laser (VCSEL) operating in the linear regime below threshold, with a reduced number of top DBR layers as shown in Fig.9.To achieve high output power from VCSOAs, large number of quantum wells (QWs) is needed. Vertical cavity semiconductor optical amplifiers (VCSOAs) has good coupling efficiency to optical fiber, compact design, polarization independent gain and are compatible with low-cost manufacturing techniques [13]. As compared to SOAs, Vertical-Cavity Semiconductor Optical Amplifiers have several advantages including higher coupling efficiency to optical fibers and lower noise figure due to their circular geometry and small dimensions [14].

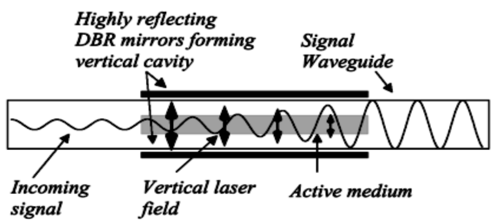

Figure 9 Vertical-Cavity Semiconductor Optical Amplifiers (VCSOA)

4) Quantum Well Semiconductor Optical Amplifier (QWSOA):

In QWSOA, the active region is a cavity sandwiched between two doped semiconductor regions with anti-reflection coating on the faces as shown in Fig.10. The signal is applied to one end of the cavity and the amplified signal is output at the other end of cavity. Quantum well SOAs have a lower differential gain coefficient compared with bulk SOAs. This leads to an improvement in the saturation output power.

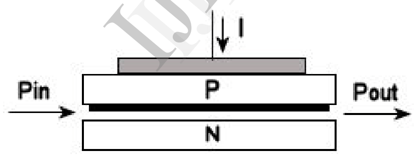

Figure 10 Quantum Well SOA

5) Quantum Dot Semiconductor Optical Amplifier (QDSOA):

The active region consists of a number of low dimensional quantum dot structures. Quantum dots (QD) are semiconductor crystals with all dimensions on the order of nanometers. The carriers in quantum dots are confined in all directions. Quantum well Semiconductor not only has freedom of wavelength choice like other semiconductor structures, but also has capability to drastically expand the bandwidth [15].

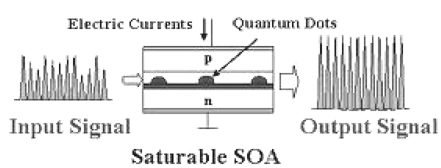

Figure 11 Quantum Dot Semiconductor Optical Amplifier

6) Gain clamped semiconductor optical amplifier:

Gain-clamped SOAs are based on distributed Bragg reflector (DBR) technology. Wavelength selective feedback is accomplished with either a DFB grating throughout the optical cavity or at the ends in which case it is called a distributed Bragg reflector or DBR mirror to create a resonant wave outside of the amplification bandwidth to stabilize the gain of the amplifier for different signal strengths. Due to this lasting resonance, the charge carrier density N saturates and the optical gain therefore saturates as well independent of the input signal [16]. The key advantage that the Adjustable Gain Clamped SOA offers over other optical amplifiers is that it enables the gain to be adjusted directly through the drive current to the clamping SOA without the dramatic loss of P_{sat} [17].

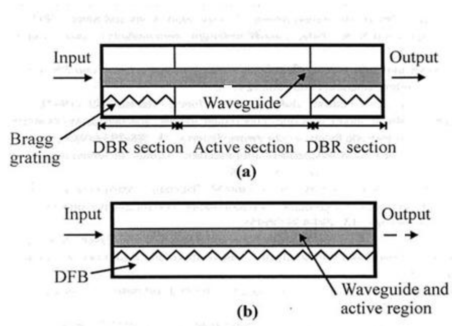

Figure 12 Gain clamped SOA (a) with DBR and (b) DFB regions

5. Semiconductor Optical Amplifiers (SOAs) as Power Boosters

There is a growing need to manage the increase in loss budgets comprising associated optical networks with optical nodes which Facilitate and Promote dynamic wavelength routing. These nodes are complex at the optical level and in order to provide the Necessary functionality, which introduces overhead loss has ramifications in respect of system designs . SOAs provide a low cost route to providing amplification in such scenarios where it is advantageous to embed the amplification within the node design or on transmitter line cards. To achieve a successful routing of wavelengths, the ability of SOA to add and drop a specific wavelength channels in a wavelength-division multiplexed (WDM) network is also a great important function [18].

6. Advantages of Semiconductor optical amplifier

Semiconductor optical amplifiers has many advantages such as compactness, Broad, choice of operating wavelength (400-2000 nm), Low price with high volume production, Low optical and electrical power consumption and non-linear gain properties [19].The major advantage of SOAs is their ability to operate at 1300nm and1500nm-even simultaneously. Semiconductor optical amplifiers are compact semiconductors easily integrable with other devices, which can also be used as wavelength converter and have a large bandwidth (up to 100nm can be covered by SOA) and can easily be integrated as preamplifiers at the receiver end same technology as diode lasers. Gain relatively independent of wavelength. Due to their compact size and fitness for integration, SOAs can be used to form gate arrays.

7. Disadvantages of Semiconductor optical amplifier

SOAs suffer from a number of drawbacks which make them unsuitable for most applications. Semiconductor optical amplifier suffers from disadvantages such as Polarization dependence, Cross-phase modulation, Four wave mixing, relatively high crosstalk, High coupling loss, High noise figure, Low output power, immature technology, technological difficulties in fabricating SOAs with low (up to

10^{-4}) reflectance's. SOAs suffer loss of linearity if their bias current and hence gain is rapidly reduced. These drawbacks make the SOAs largely unsuitable for multichannel WDM applications.

8. Conclusion

It is concluded that SOA is characterized by extremely strong non-linearity, low power, high operation rate and small size. 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. 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,dispersion compensation and wavelength conversion in WDM applications

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Biography

Aruna Rani was born in Guru Har Sahai (Ferozepur), Punjab, India, on 16 March 1992. She obtained her Bachelor's degree in Electronics and Communication Engineering from Shaheed Bhagat Singh state technical campus, Ferozepur, Punjab, India. She is currently a full time M.Tech scholar in Electronics and Communication Engineering Department at Shaheed Bhagat Singh State Technical Campus Ferozepur, Punjab, India. Her research mainly focuses on Optical Communication Systems and Semiconductor optical Amplifiers.

Sanjeev Dewra was born in Panagarh (West Bengal), India, on October 22; 1971.He received a B.E (Electronics & Telecomm.) degree from Mahatma Gandhi Missions College of engineering & technology, Marathwada University, Aurangabad (M.S) in 1993 and a M.E. degree from GNDEC, Ludhiana in 2002. He is currently working toward his Ph.D. degree at Thapar University, Patiala (Punjab). His field of interest is optical add drop multiplexer & optical cross connect for optical communication systems. He has published various research papers in international journals & conferences. Mr. Dewra is a life member of the Indian Society for Technical Education, Institution of Engineers (India). He has over 20 years of Education Experience. He served as lecturer in Saint Kabir Institute of Pharmaceutical & Technical Education, Fazilka from 1994 to 1998. He then joined Lala Lajpat Rai Institute of Engineering & Technology, Moga as a lecturer in 1999. In 2000, he joined Giani Zail Singh College of Engineering & Technology, Bathinda (Punjab), as Lecturer in the Department of Electronics and Communication Engineering and continued till 2003. In 2003, he joined as a Lecturer in the Electronics and Communication Engineering Department in Shaheed Bhagat Singh College of Engineering and Technology, Ferozepur (Punjab) & became a senior Lecturer in 2005. Presently he is working as an Assistant Professor & Head of ECE Department in the same college.