Malik, Yasir (2014) *Gain control in semiconductor optical amplifier*. MSc(R) thesis

University of Glasgow | School of Engineering

Gain Control in Semiconductor Optical Amplifier

Yasir Malik

August 2014

A thesis submitted in partial fulfillment for the degree of

Master of Science by Research (MS-Res)

in the

College of Science & Engineering

School of Engineering

Declaration of Authorship

I, Yasir Malik, declare that this thesis titled *"Gain control in Semiconductor Optical Amplifier"* and the contributions presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.

Yasir Malik

23-August 2014

Everything is determined, the beginning as well as the end, by forces over which we have no control. It is determined for the insect, as well as for the star. Human beings, vegetables, or cosmic dust, we all dance to a mysterious tune, intoned in the distance by an invisible piper.”

Albert Einstein

Abstract

This thesis is concerned with the study of characteristics of commercial Semiconductor Optical Amplifiers-SOAs and their employment in GPONs for the purpose of packet equalization of upstream bursts in order to provide additional loss budget. Additional loss budget is aimed at facilitating the extension of GPONs to provide not only longer distance between central office and end user, but is also expected to increase the number of maximum users that can be connected to a single central office.

The problem and the requirements of optical networks are described. After careful investigation into legal and technical dimensions of the situation such as use of certain wavelengths and EDFA's inabilities, it is concluded that instead of EDFA or an Opto-electronic amplifier, an SOA should be considered for the purpose of employing as an optical amplifier installed in front of burst mode receiver at the central office.

Commercial SOAs are used in order to investigate the limitations of SOA so that a suitable solution can be looked for within the functional constraints of the amplifier.

The results of parametric measurements including input/output signal power, Gain and saturation are discussed; four different commercial SOAs are assessed with special emphasis on input power dynamics and gain response.

The bit error rate -BER analysis is performed on SOAs in the context of the findings of parametric analysis of the SOAs. The effect of varying the input signal power on BER was observed. The receiver sensitivity for BER of 10^{-9} was measured for various SOA input power values. Power penalty imposed on receiver's sensitivity, by saturation effects and noise is analysed.

Contents

List of Figures

Chapter 1: Introduction

1.1 Background

The concept of communication or transmission of message is as old as the life on earth. Humans, animals and even plants communicate [1] with each other using their own means. A honey bee when finds food stock, performs a specific dance in front of fellow nest mates, who can interpret the encoded steps to locate and assess the food reservoir [2]. The story found in the holy books describing the first introduction between Adam and Eve on the mount Arafat is termed as first communication between two human beings on earth. With the passage of time, as the civilizations evolved, communication and modes of communication between human beings also developed. Smokes signals, drum beats, pigeon messaging, messaging through pictures and signs, and use of flags were the major modes of sending information that have been in use for thousands of years. The post office department as a mode of sending the information available for commoners has also been reported to have been maintained by numerous ancient empires in history especially Romans and Persians.

The sending and receiving of information through electrical signals is a revolution in communication industry that started in 19th century by the advent of telegram system. Telegram uses pulsed electrical signal which is decoded at receiver's end [3, 4]. The invention of telephone by Alexander Graham Bell in second half of 19th century provided a platform for two way voice communication. The conventional analogue telephones ruled the communications industry for almost a century. Although a number of developments in telecommunications were in progress during this period, until as recently as 1980s the classical analogue telephones were the only widely available and publicly used means of communication that allowed live conversation [5]. In most parts of the world having a phone connection at home used to be privilege, and it was not uncommon to find a civilized village or town with no or single phone connection. Many people had to travel tens of miles to make a telephone call. Calling abroad or even long distances within the country would be very costly. An alternative to telephone was 150 years old telegram system which was cheaper than telephone, and would convey the message in couple of hours, thus was faster than the conventional post office mail [6].

In last 30 years, the telecommunications industry has seen enormous progress. Mobile phone and internet are the most popular examples of the advancement during this period. Internet became globally popular among general public in late 1990s [7, 8] and had a significant impact on cultures and businesses as it provided an instant means of communication using email [9-12] and instant messaging services, instant access to online literature, online discussion forums, video calling, and file sharing and transfer. Voice over Internet-Protocol –VoIP was developed as protocol to transport voice calls over internet [13]. Internet users use VoIP based internet service such as Skype [14] to make free internet calls whereas the telephone companies use VoIP as a vehicle for transporting phone calls [15]. In 1990s and early twenty first century, internet was mostly accessed through dialup connection using a dialup modem with maximum speed of 56 kb/s [16, 17]. With dialup connection it was unimaginable to run or download full movies or videos as it took about 15-30 minutes to download a 5 MB file. Now-a-days dialup is the choice only for people living in remote areas where broadband services not yet accessible. Broadband is a major breakthrough in cyber industry [18, 19]. Live video streaming [20, 21] and movie downloading became very easy with 100 Mb/s data rate. Internet TV, live channels, internet gaming, video streaming and online gaming have become the major consumers of the internet these days.

In wireless communications, mobile phones are the most publicly used development [22]. Now-a-days for many people it is difficult to imagine a normal life without a cell phone. Mobile phone technology was in progress in 1970s though, the very first commercially automated cellular mobile network, using the analogue advanced mobile phone system-AMPS, later on referred to as first generation or 1G standard, was launched in Tokyo-Japan in 1979. Within next few years the AMPS mobile network was not only expanded to all cities of Japan, but many other countries including Denmark, Finland, Norway, Sweden, and USA launched their own mobile networks, followed by UK, Mexico and Canada in the mid 1980's. By early 1990s AMPS mobile phone networks had been established in most countries around the globe. Second generation - 2G digital cellular telecom networks were commercially launched on the Global System for Mobile Communications -GSM standard in Finland in 1991. The GSM was not only faster and reliable but also economic. The cell size had to be decreased thus increasing the number of base stations; which however was not a problem anymore as the equipment required had also become inexpensive. In addition to voice calling service GSM also provided data transfer services initially based on circuit switching later on replaced by general packet radio service - GPRS. GSM data transfer services could be used for fax, short messaging service -SMS and very high data transfer rate allowing live streaming and video calling. Although most of the mobile service providers still use 2G or GSM standard, third generation or 3G based cellular networks are also in practice. In UK, the company named *'Three'* started the first 3G network [23]. The later releases 3G technology, i.e. 3.5G and 3.75G mobile offer higher data rates, specialising in mobile television and high speed mobile broadband.

Since the cost of both the handset and phone services has become affordable for people from almost every section of society, there has been a considerable increase in the number of subscribers over last decade. In Oct 2012 GSM Association announced the total number of mobile users to be 3.2 billion which meant that 45% of world population is connected through mobile phones [24].

However the progress in the front end technologies including the ones described above has only been made possible with optical fibers in the backbone system. Optical fibers provide a very high speed transmission medium to transport all the data between cities, countries and continents [25]. The optical fibers carry the data signal which is carried by a beam of light and guided along the length of the fiber based on the principle of total internal reflection. The electrical signal is converted into optical signal using a light source mostly a laser or an LED. The light is received at the receiving end by a light detector which converts the optical signal back to electrical signal. As the signal gets attenuated by travelling along the fiber, repeaters are used after a specific distance to regenerate the optical signal [26].

First installation of optical fibers dates back to April 1977 when the company General Telephone and Electronics sent first live telephone traffic through optical fiber at data rate of 6 Mbit/s in Long Beach, California. In Britain, the same year in June the British post office started telephone over optical fibers in Martlesham Heath [27]. At that time optical fibres could not be employed at large scale in communications systems because of very high losses (excess of 1000 dB/km) [28-31] and small repeater spacing (maximum 10km). First formal fiber system started in 1982 with 52 Mb/s initially at 850 nm and later on switched to 1300nm[27, 32]. However this was not still enough to compete with coaxial data cable that provided data rate up to 560 Mb/s [33]. Around 1988, advancement in fibres led to deployment of fiber in backbone systems with speeds 140 Mb/s & 560 Mb/s. By that time optical fiber was able to carry the light signal without need of regeneration for 52km, thus surpassing the span of coaxial cable. Shifting to 1550nm windows from 1330nm resulted repeater spacing to increase to 90km. The same year first transatlantic underwater optical cable TAT8 was laid between US and Europe connecting US, UK and France. With a data rate of 280 Mb/s and repeater spacing of 120km clearly provided a better solution than traditional coaxial cable. Later on in 1990s TAT9 (1992-2004), TAT10 (1992-2003), TAT11 (1993-2003), and

TAT12/13 (1996-2008) were installed and remained in use. In year 2000 TAT14 connected the Americas and the Europe with 3.2 Tb/s data rate and is still functional.

One of the major achievements in the field of optical communication in 1990s was the ability of fiber to carry data at a rate as high as 2.5 Gb/s – at transmission wavelength of 1550 nm with a repeater spacing of 100 km. Research work began on 40 Gb/s in early 2000’s [34]. Now-a-days systems with data rates up to several Tera bits per second are commercially available [35, 36].

The above paragraphs discusses some of the examples of the front end technologies and applications exploited by the end users, along with the brief introduction of backend optical fibers used as backbone in long haul transmission. However equally important are the access networks which provide link and manage the data traffic between the long distance fibers and the front end service providers. The complexity and importance of the access networks can be understood by comparing the telecommunication system with the analogous real life road transport. The highways and the local area streets are easier to manage, but the metropolitan area roads that link local areas with each other, and local areas to the highways, are relatively complicated and need greater deal of traffic management, thus bottlenecking the performance of rest of the transport system. Similarly in modern optical telecommunications the access networks bridge the long haul fibers links and the front end service providers [37, 38]. With optical fiber industry looking up to data rates of the order of Tera Bits per second-fibres is far ahead of the current load accommodation profile [37]. Similarly the front end telecom service providers e.g. the cell phone, internet service providers –ISP etc manage and control the data their way within their own frame work. A large variety of data traffic comes from different users and it is then upon the access networks [39], that the data is properly gathered and transmitted to the main fiber line, and the incoming data is correctly received and routed to desired locations. As the bandwidth capacity of the optical fiber is very large as compared to the electronic base rate of 10 Gb/s, the multiplexing techniques are used in optical domain. Most common of these are ‘Wavelength Division Multiplexing’ WDM [40] and ‘Optical Time Division Multiplexing’ – OTDM [41]. In WDM a unique wavelength is allotted to a signal for transmission into optical fiber. Being less complex, WDM systems are easily implemented, and thus systems with capacity of several terabits per second are commercially available [42]. A further development of WDM is ‘Dense WDM’ -DWDM in which closer wavelengths are used, thus increasing the number of channels within a wavelength spectrum [43].

Optical code division multiple access -OCDMA is another multiplexing technique in which users are assigned unique coding sequences [44, 45]. As the data is encoded, multiple users cannot only share the same fiber channel, the bandwidth is also efficiently utilized. Single chip semiconductor OCDMA circuit are being investigated for telecom networks which is expected to be cost effective, compact and efficient [46].

At metropolitan level passive optical networks -PONs have been introduced in which optical fibers are connected using splitters [47] and are used for point-multipoint system [47, 48]. In PONs data from different fibers can be gathered into a single fiber and vice versa without the need of any electrically powered equipment. Giga bit PONs or GPONs are PON networks designed for data rates above 1 Gb/s [49].

The inline amplification of attenuated multiplexed data in the fiber channel was the next task. In the beginning, optoelectronic repeaters were used [50, 51]. An optoelectronic repeater converts the weakened optical signal into electrical signal, amplifies in electronic domain and re-transmits using optical transmitter. In order to amplify the optical signal containing WDM channels, the data had to be de-multiplexed first into separate n-channels, amplified in electrical domain, again multiplexed and retransmitted. The process would require almost the same complications as that of the main receiver or transmitter end. The introduction of optical amplifiers, initially semiconductor optical amplifier-SOA followed by erbium doped fiber amplified –EDFA in mid 1980s [52, 53] solved the problem by making signal optically transparent. SOAs are electrically pumped and use a semiconductor material as amplification medium. EDFAs are optically pumped fibers amplifiers, that use a length of fiber with core doped with a rare earth material.

1.2 Focus of thesis

This thesis is concerned with measurements and study of SOAs and investigation of their role in possible reach extension of GPONs. An optical amplifier is required which can not only amplify very high speed data, but should also be able to switch to a different level of amplification at a very high speed as different bursts of data coming from variety of sources may need different gain. In this way, the number of end users can be increased from 32 to 128 and OLT-ONU distance be increased from 20km to 60km, as per defined and allowed by the ITU standard for GPONs.

EDFAs have always been a good choice for inline optical amplification. However the EDFAs normally work in saturation region and have a gain recovery time greater than the bursts' length. SOAs with small recovery time make a better case for use as an inline amplifier for upstream burst mode traffic in GPONs. In addition, in certain countries including United States, the legal restrictions on use of 1550nm band to Cable TV also restrict the use of EDFA. The issue is discussed in further detail in Section 4.1.

A parametric and bit error rate-BER analysis of the system using SOA is presented with focus on constraints imposed by gain saturation, noise and power penalty. This work is intended to guide and ease the future research in employment of SOA as amplifier in front of burst mode receiver for the purpose of extension of GPONs.

1.3 Novel Features of this research work

In the author's view, the main points of the thesis are:

- Investigation of the saturation behavior of numerous commercial SOAs with different active region lengths, photoluminance wavelengths, and facet reflectivity, and their analysis and comparison in the context of automatic power and gain control
- Parametric and error rate analysis of SOA to assess its feasibility for perspective extended GPONs.

1.4 Structure of Thesis

Chapter 1 gives a general review of the optical communication technology, history and achievements. The chapter starts with background of optical communication system describing its main components like optical fiber, transmitter and receiver. It is followed by the description of the need of optical amplification and introduction of different kinds of optical amplifiers. Multiplexing techniques like WDM, OTDM and OCDM are then discussed. Later part of the chapter encompasses the GPON network and the anticipated extended GPON that provides the ground for this research.

Chapter 3 is an introduction to the SOAs. The chapter starts with the introduction of semiconductor lasers as basis for the SOA technology. After that a brief description of structure of SOA is provided along with the basics of amplification process of the device. After that different types and structures of SOA, anti-reflection coatings and other antireflection techniques are described, followed by a discussion on basic parameters vital to SOA operation like gain, gain saturation, saturation power, signal to noise ratio, and input saturation power etc are briefly described.

Chapter 4 describes the basic parametric measurements performed on commercial SOAs. The parameters of the SOA studied in these measurements include input and output optical power, gain, drive current, signal wavelength, and saturation power. Since the main features of the SOA defining its characteristics are gain, saturation and dynamic range, these have been discussed in detail. After the analysis of a typical commercial SOA, measurements on 4 different commercial SOAs are discussed for the purpose of comparison and analysis. The trade off between small signal gain and input saturation power of the SOA is discussed.

Chapter 5 discusses bit error rate measurements on an optical system containing SOA. This time an optical signal comprising of PRBS data is used instead of continuous wave probe. Issues like receiver sensitivity and power penalty imposed by amplification process are discussed in detail. Power penalty analysis gives a better picture of the constraints posed by amplification and the ranges over which the device could be used.

Chapter 6 includes summary of the thesis, major conclusions and recommendations for future work to be continued on the topic.

Chapter 2: Optical Communications

2.1 Introduction

This chapter provides a brief description of the basic components used in optical communication systems. An introduction to optical amplifiers along with a discussion on GPONs and extended GPONs is given that provides a background for this research work.

2.2 An Optical communication system

In optical communications system, the data is transported by light signals that travel through a suitable channel, normally an optical fiber. This provides transmission of data over long distances with higher speed and bandwidth as compared to the other media used for telecommunications. An electrical signal is modulated onto a carrier light (e.g. the light from semiconductor laser) using opto-electronic modulator (e.g. Mach-Zehnder modulator). The light wave carrying signal then travels in the optical fiber and is then received at the other end by a light wave receiver (photo detector) which then converts the light back to electrical signal [54].In order to utilize the capacity of an optical fiber to the maximum extent, several electrical channels are multiplexed onto a signal fiber channel using either optical time division multiplexing - OTDM or wavelength division multiplexing – WDM .

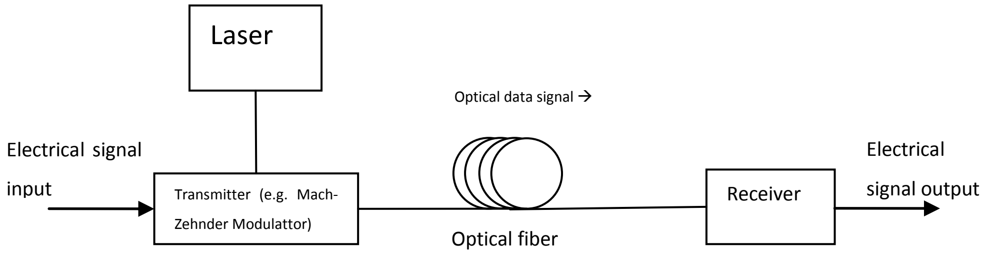


Figure 2-1: A Schematic of basic optical communication system

Over long spans of optical fiber channel, the optical signal attenuates due to dispersion, bending losses [54], fiber imperfections [55] and polarization mode dispersion [56]. Amplifiers are used to regenerate the signal after a certain distance [57]. Optical amplifiers e.g. Semiconductor Optical Amplifier - SOAs and Erbium Doped Fiber Amplifier - EDFA are good choice for inline amplifiers as they provide receiving, amplifying and retransmission in optical domain without converting the signal to electrical [37, 58]. Figure 2.1 depicts the schematic of the basic optical communication system.

2.3 Optical Fibres

Optical fiber is a transparent conduit made of glass or plastics, designed to transport light waves along its length. An optical fiber consists of three coaxial regions: the inner most region is called the core, which is surrounded by middle region known as cladding. The outermost region is called the sheath. The core always has a higher refractive index than the cladding, and due to the total internal reflection the light is confined inside the core. The sheath serves as a protective jacket which protects the fiber from ambient effects.

As we can see from Figure 2-2 a ray of light is entering the fiber at an angle θ_1. If θ_1 exceeds a certain value known as angle of acceptance, the total internal reflection will not occur and the light will be lost into the cladding. The angle of acceptance defines the input cone and/or numerical aperture of the fiber

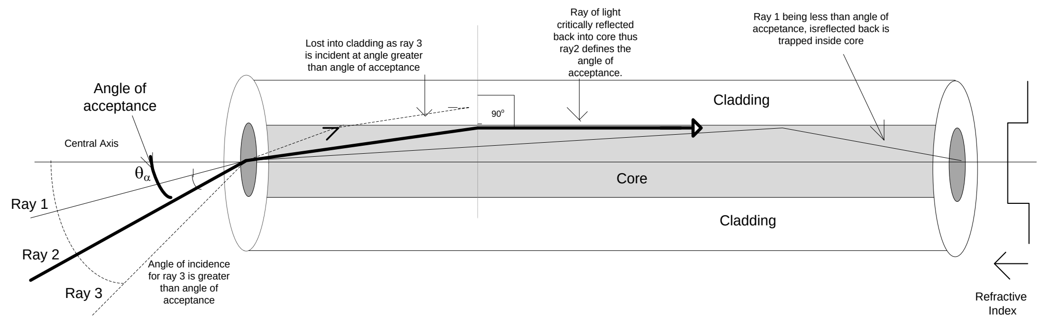


Figure 2-2: Light travelling inside an optical fiber

Angle of acceptance - θ_α can be derived by considering the ray 2 which refracts at 90^0 on the junction of core and cladding, as shown in the Figure 2-2. By assuming the medium outside the fiber as air and applying Snell's law at air-core and core-cladding junctions we get numerical aperture of the fiber N.A.:

$$\sin\boldsymbol{\theta_\alpha} = \sqrt{\mathbf{N_{core}}^2 - \mathbf{N_{cladding}}^2} = \mathbf{N.A.}$$

Equation 2.1

$$\boldsymbol{\theta_\alpha} = \mathbf{Sin^{-1}}\left(\sqrt{\mathbf{N_{core}}^2 - \mathbf{N_{cladding}}^2}\right)$$

Equation 2.2

Here N_{core}, and $N_{Cladding}$ are the refractive indices for core and the cladding respectively, and $\boldsymbol{\theta_\alpha}$ is the angle of acceptance. As we can see that acceptance angle of a fiber depends upon the value of refractive indices of the core and cladding, by using material with specific refractive indices, angle of acceptance can be chosen.

When light enters into an optical fiber, every ray of light with incident angle less than the acceptance angle will be allowed to propagate along the fiber. The allowed paths or directions that are followed by the rays of light inside the fiber are called modes of propagation. The fibers that allow more than one mode are called Multimode fibers. Multimode fibres have core diameter of around 50 microns. However, such fibers may exhibit intermodal dispersion [59]. Single mode fibers are designed to allow a single ray of light within the optical fiber. They have a core with very small diameter (2-10 microns). In addition to the step index fibers discussed above, there exists a variant of multimode fiber known as graded index fiber in which the refractive index of the core is not constant and varies along the diameter with peak in the middle. Figure 2-3 depicts structure of a single mode fiber, multimode step index fiber and a graded index fiber.

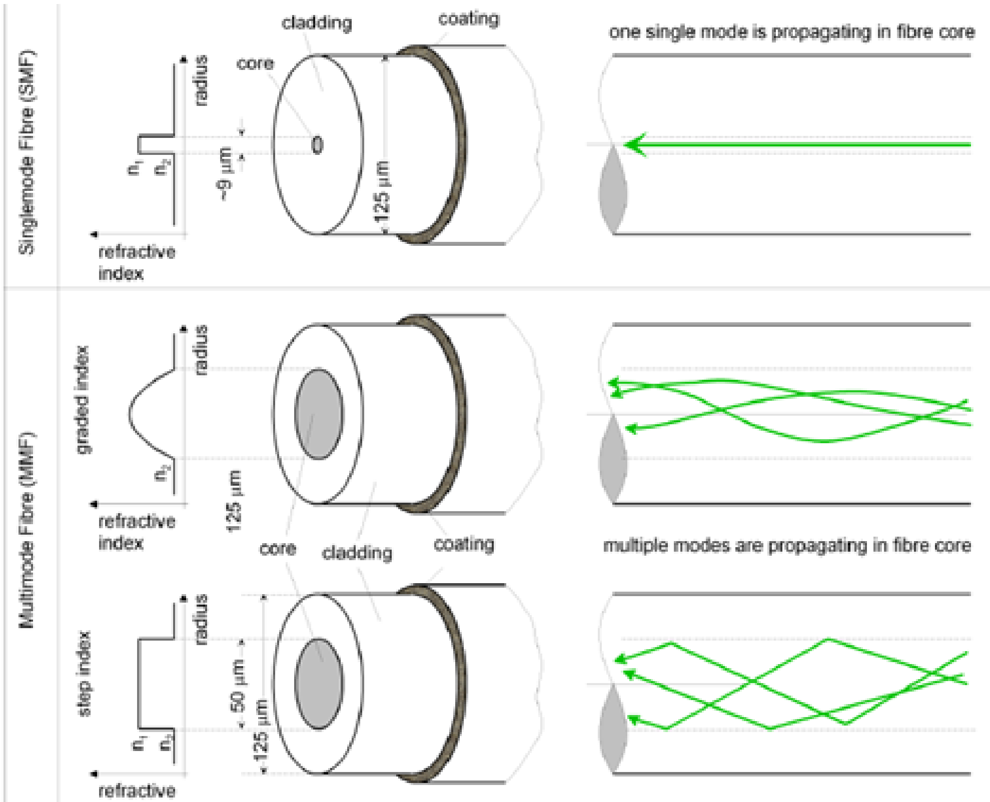


Figure 2-3: Single mode, graded index, multimode fibers (Courtesy: Werner Rosenkranz, Digital communications

The choice of material for optical fibers depends on the application. For the purpose of data communications over long distances, silica glass fibers are used as they offer low loss propagation for long wavelengths, particularly around 1550nm where the losses are as low as 0.2dB/km [60]. Transparency for other wavelength regions can be increased by varying the concentration of hydroxyl groups – OH.

In silica fibers, both the core and cladding are normally doped to achieve the required refractive indices. Doping of certain oxides e.g. Germanium dioxide (GeO_2) or

Aluminium oxide Al_2O_3 increases the refractive index, whereas doping of Boron trioxide (B_2O_3) decreases the refractive index of the silica fiber. Hence by engineering the material used, the angular width of cone of acceptance of the optical fiber can be chosen [61].

Plastic optical fibers that are made of poly methyl methacrylate - PMMA (commonly known as acrylic glass) have relatively higher attenuation and distortion as compared to the silica fibers [62]. As these fibers and the associated accessories are relatively inexpensive, they are commonly used for low speed and short distance applications such as local area network, sensors and device probe connectors etc. Recent developments suggest plastics fibers suitable in communications for distance up to 100m with data rates above 1 G b/s [63].

2.4 Repeaters and amplifiers

Repeaters and amplifiers are important components of modern optical networks. An optical signal attenuates after travelling a certain distance and therefore needs to be amplified or regenerated. In opto-electronic repeaters the optical signal is detected by a light receiver, electrically amplified and then converted back to optical signal [50, 51]. With the advent of WDM in optical communication the optical-electrical-optical -OEO repeaters became less popular as they required every channel to be de-multiplexed, amplified separately and multiplexed again. In addition, the slower speed of the electrical domain would also bottleneck the communication at repeaters. The issue was quite successfully addressed by the EDFA [64] which provided the solution to amplify the optical signal without converting it to electrical domain. EDFA also amplifies all the WDM channels simultaneously without separating them [65, 66].

An alternative to EDFA is Semiconductor Optical Amplifier – SOA. An SOA is similar to a semiconductor laser with anti reflection measures on facets to keep the radiation from resonating [67-69]. SOAs are small in size and can be integrated with other optical components including lasers and modulators. SOAs are integrated with semiconductor laser to increase its output power [70, 71].

2.5 Passive Optical Networks - PONs

A passive optical network-PON is optical network architecture for optical access-networks. PONs are based on point-to-multipoint transmitting and receiving. The word ‘passive’ refers to the fact that the splitters used to connect the fiber into multiple lines and junctions are not powered. PONs are based on physical layer architecture. For downstream transmission, PONs use one-point-to-multipoint physical topology.

Similarly for upstream they use multi-point-to-one-point topology [72, 73]. There are number of advantages of PONs over the other networks; for example PONs are economic because of less number of transmitters and receivers – single transceiver is used for all the users at junction. Different multiplexing techniques including WDM [74] and OTDM [75, 76]etc can used to connect multiple users.

Other significant advantages of PONs include agility, high capacity, eliminations of costly optical-electrical-optical -OEO conversions, minimized transceivers, and making fiber to the home- FTTH [77] easy to implement [78, 79]. Figure 2-4 shows an optical network with local network implemented as PON.

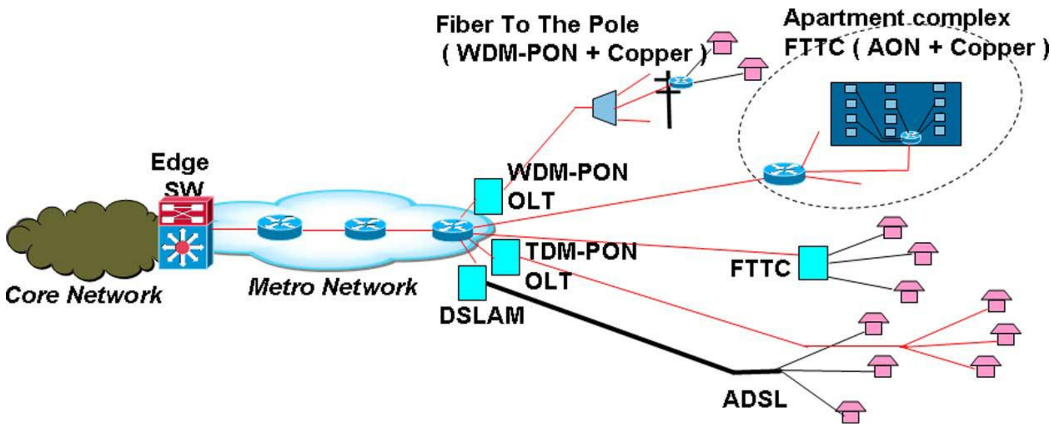


Figure 2-4: A schematic showing an Optical Network with Passive Optical Network at access level (Right hand side of figure is PON). Taken from [80]

2.5.1 PON Architecture

The three main basic components within the PON architecture are:

- OLT – Optical Line Terminator:
- Passive Optical Splitter
- ONU - Optical Network Unit

OLT is the end of single mode fiber coming into the area and from here the PON architecture starts. A single fiber runs from the OLT to a passive splitter which is located near the users' locations. The optical splitter merely divides the optical power into N separate paths to the ONUs. The number of optical paths can vary between 2 to 128. From the Splitter a separate fiber goes to every ONU. The ONU then converts the data into required form for the user. Figure 2-5 illustrates the basic architecture of a PON for an access network.

The data format and frame architecture for different kinds of PONs are different and are best described in context to the PON type. However, because this thesis is mainly related to GPONs, after discussing a few types of PONs we will discuss the frame format for GPONs in detail in a later section.

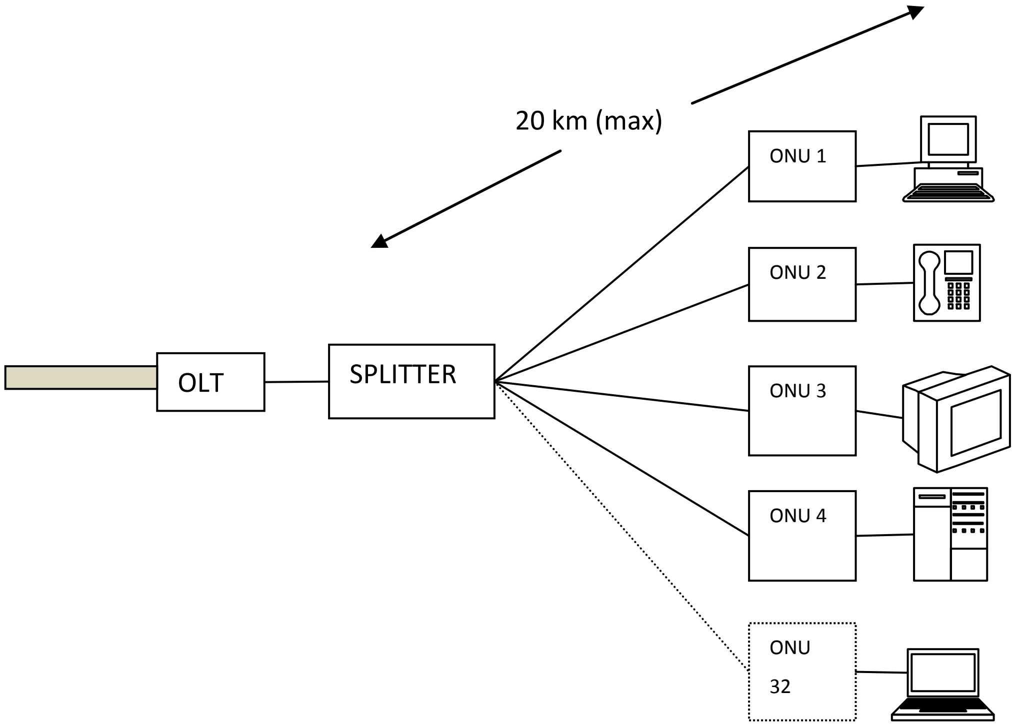


Figure 2-5: Schematic of PON Architecture

2.6 Gigabit PONs -GPONs

2.6.1 Introduction

As the name suggests, Gigabit-PON is a PON protocol particularly designed for transporting data rates on the order of several giga bits per second. Using larger and variable length packets, a GPON manages to utilize the bandwidth for higher number of services and users. For real time delay sensitive services like voice and video communication traffic, GPON uses frame segmentation, a strategy similar to small cells of ATM networks, thus offers efficient packaging of user traffic. [81]. GPON is more efficient than other PON architectures like APON and EPON and offers 40% to 160% additional bandwidth, depending on the specific application and supported services [82]. GPONs are very cost effective, because not only is the system cost itself low, but also the higher efficiency leads to much more 'revenue bits' from the same system, and a much shorter payback period [83].

Compatibility with preinstalled infrastructure is always an issue for emerging technologies. GPONs can easily be adjustable to new services without making changes to the GPON equipment. World's first field trial of 10G-PON (also known as XG-PON) has recently taken place which can deliver 10 Gb/s downstream and 2.5 Gb/s upstream to residential or business customers. The trial confirmed XG-PON [84]. In order to put discussion on motivation of this research in context, GPON Network Architecture will be discussed in Section 1.7 along with perspective extended reach GPON architecture.

2.6.2 Optical Burst Switching in GPONs

As discussed above the developments in different sections of the optical networks are continuously in progress. After the struggle between pros and cons of the classical circuit switched network and modern packet switching for a very long time [85], the burst mode switching of packets is now making its place in the industry [86, 87]. Burst by definition is series of repetition of an event occurring adjacent to each other without any delay or any other event occurring in-between. A popular use of the term 'burst' is the 'burst of bullets' from an automatic machine gun when operated in automatic mode. In computer network language the burst switching refers to the burst of data packets transmitted adjacent and in one go from a single source. The topology has already been in practice with its applications ranging from satellite communication and communication between the components within the computer like hard disk drive, temporary memories, and processor etc [88]. The same topology is now being applied in optical networking.

In burst switching, a number of data packets travel in a single burst. Because all the packets have the same control information, there is no need for individual overheads. For a number of burst mode data channels, a single control channel is allocated [89-91]. This control information is always ahead of the data channels by a time difference known as offset, in order that the receiver can be adjusted according to the incoming burst information [92]. The information about the burst carried by the control channel includes routing details, length of burst etc. Though the bursts of optical data remains optical, the control channel is received and converted to electrical signal for purpose of adjustment, according to information contained at the receiver end.

2.6.3 Extended Reach GPON

GPON network follows the ITU-T G.984 standard. GPON standard as per defined by ITU allows up to 128 ONUs and [93] a logical fiber length of 60km. However in practice GPONs are restricted to a maximum of 32 users and a maximum OLT-to-ONU length of 20km. All the 32 users are restricted to be within a 28dB tolerance [94] (also known as loss budget) from the burst mode receiver installed in the central office. Hence the burst mode receiver at central office is able to receive the data bursts without need of further amplification. Recently there has been much interest in increasing the loss budget of GPON. By increasing the loss budget both the distance between OLT and ONU, and the number of ONUs can be increased.

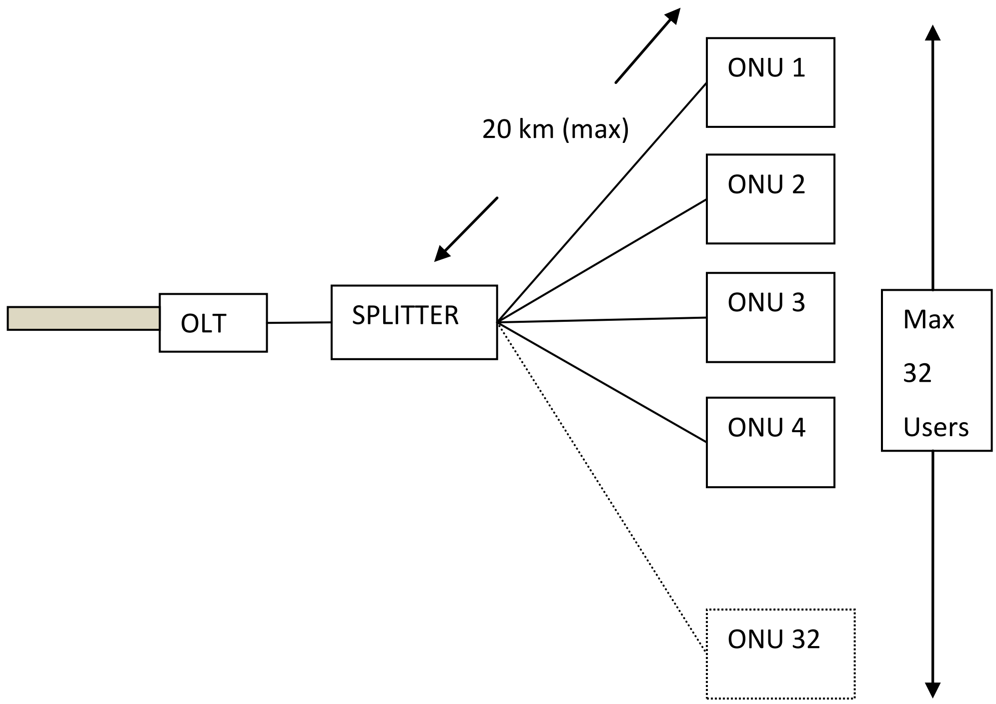


Figure 2-6: GPON currently in use

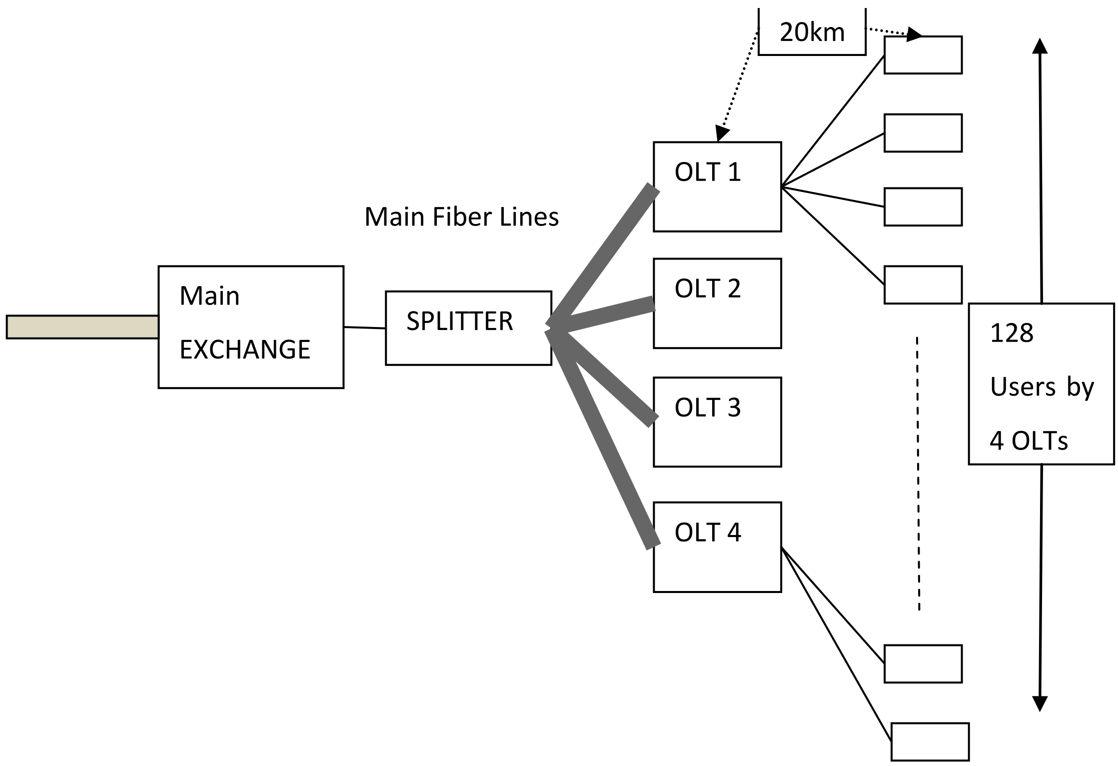


Figure 2-7: Metro network of 4 OLTs with GPON access units

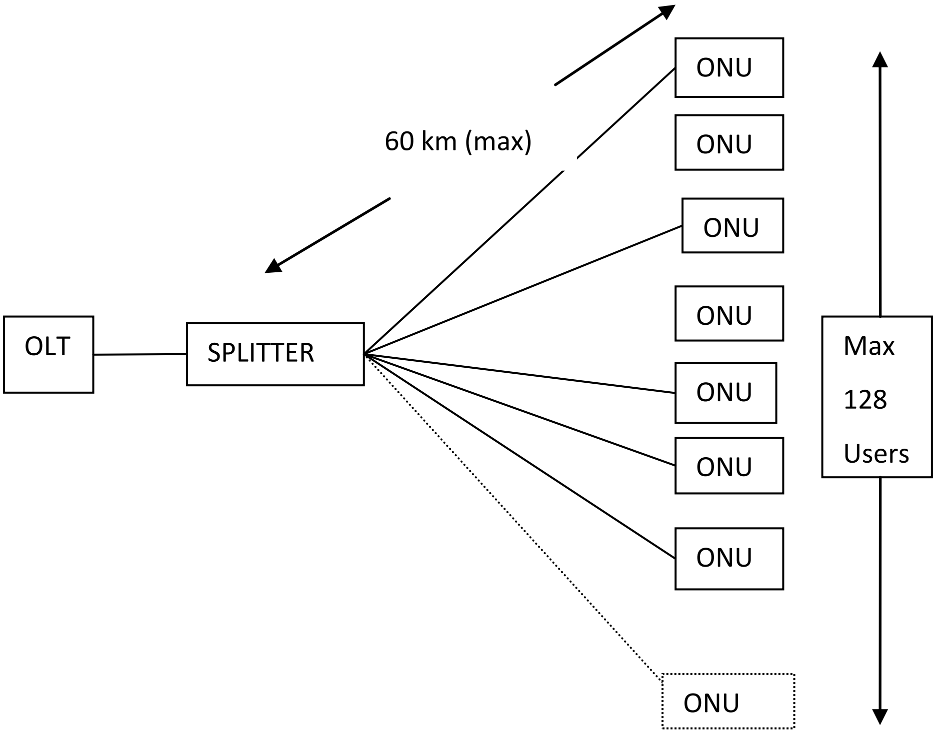


Figure 2-8: The perspective extended GPON, replacing the Metro network shown in Figure 2-6

Figure 2-6 shows an example of the current GPON architecture. In order to provide services to 128 users, 4 OLTs are required and the user must not be more than 20 km away from the respective OLT. In any case either if the end user is more than 20km away from the OLT or the number of users for an OLT exceeds 32, a new OLT will be required for the user to be connected.

Figure 2-8 is the replacement of the metropolitan area optical network of Figure 2-6 by an extended GPON. The benefit of increased ONU's is obvious that with lesser number of OLTs more users can be entertained within the access network. Increasing the logical fiber distance from 20km to 60km is also vital to both the service providers and the end users. The service providers will benefit by linking more ONUs to single OLT thus decreasing the need for real estate etc., close to end user and making service more centralized by taking the OLT to the even higher levels. Extended reach service will also be beneficial for users who live far from urban area.

For the purpose of extension of GPON to its maximum capacity, the loss budget has to be increased from 28dB for the upstream data traffic from ONUs. The burst mode receivers however are not yet able to handle the variety of bursts with losses exceeding from 28dB. Hence an amplifier is required which can not only amplify the upcoming bursts but also be able to change its gain to handle different sized bursts coming from different users.

In upstream traffic different bursts come from a number of different users that are behind their ONUs. Different bursts of data are of different sizes and hence require different level of amplification in order to equalize for the purpose of sending to OLT or the central office.

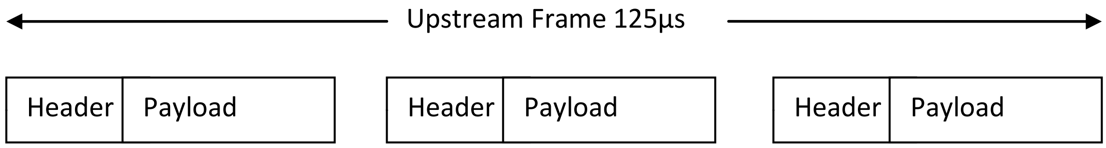


Figure 2-9: Frame format for upstream data traffic in GPON

GPON frame format for upstream traffic is shown in Figure 2-9. The Upstream GTS frame duration is also 125us and is 19440 Bytes long, which gives an upstream data rate of 1.24416 GB/s. However an upstream frame is shared among ONUs which contains a number of transmission bursts coming from one or more ONUs.

Every upstream data burst contains a header and a payload. The Header contains routing, addressing, and synchronizing information, whereas the payload contains data [95]. On the leading end of the payload is a section called preamble. The preamble leads the whole GTC frame [96]. The preamble is a general bit sequence may be or not may not be known to the burst mode receiver. The burst mode receiver acquires the clock and other synchronization parameters from the preamble and compares the bit sequence for adaptive equalization in order to rectify the distortions inflicted by the channel. The preamble also allows the repeater burst mode receiver to adjust gain and threshold for the incoming burst [97]. The received data is then amplified by the opto-electronic amplifier. In this process some of the preamble is used up and lost. However, rest of the preamble and the frame is then received and forwarded properly. If a single frame has to go through a series of burst mode receivers with every receiver consuming a chunk of preamble, the GTC frame might completely lose the preamble. This situation is undesirable as the following receiver in this case will treat the front bits of the remaining frame as preamble resulting in loss of information. It is difficult to acquire clock and data recovery fast enough without eroding the preamble. Therefore for the case of opto-electronic repeaters, the maximum number of receivers, the GTC frame can be received (and forwarded) in series is limited by the length of preamble and the proportion consumed by every receiver.

On the other hand the optical amplifier can amplify the stream without knowing what is inside the frame and without consuming any part of it. Therefore, optical amplifier is a good choice as amplifier to be installed in front of the burst mode receiver for amplifying the upstream data traffic in perspective extended GPONs.

Optical amplifiers on the other hand have other issues that need to be addressed. The predominant optical amplifier so far is EDFA that has fairly good performance as a transparent optical amplifier. However, for the burst mode amplifier EDFA is not a good choice because of its large gain recovery time which is on the order of a few milli seconds. The standard length of a GPON frame is 125μs that is far smaller than the recovery time of EDFA. Due to very high gain recovery time the EDFA cannot switch gain fast enough to full fill the varying amplifying needs of the different sized optical burst coming from different users.

The SOA with gain recovery time of the order of nano seconds can be easily fabricated for any specific range of signal wavelength. Therefore for the purpose of reach extension in GPONs, SOA makes a better case. Further discussion on the comparison of SOA and fiber amplifier can be found in Section 4.1.

Saturation characteristics and gain control of SOA are issues that still need to be addressed. It is difficult to manage to control the gain of SOA, especially because of saturation at high signal powers. Therefore this thesis is focused on the study of behaviour of SOA in the context of its application as amplifier in front of burst mode receiver.

Chapter 3: Semiconductor Optical Amplifier

3.1 Introduction

This chapter describes the basic semiconductor physics that is necessary to understand the operation of SOAs and how various aspects of its operation can be controlled and improved. An SOA is a variant of semiconductor laser and the lasing process in both the devices follows the same basic principles. Therefore, this chapter begins with a brief overview of semiconductor lasers and their working principles in order that the discussion on SOAs could be understood. Rest of the chapter describes structure and operation of SOAs, SOA characteristics like gain and saturation, and the factors that affect the performance of SOA employed in optical networks.

3.2 Semiconductor lasers

Since their invention in 1960s [98] semiconductor lasers are perhaps the most popular and widely used lasers with their use ranging from toys, instrumentation, pointers, medical treatment, masonry measurements, weapons aiming and guiding systems, and telecommunications [99, 100]. The lasing wavelength is mostly application specific. Most of the applications require the laser in visible range as to guide the human sight. In telecom, however instead of visibility, low loss transmission of data through an optical fiber is generally required, which occurs at the low loss windows of 850nm, 1330nm and 1550nm [101]. Out of these three low loss windows only 850nm wavelength lies in visible region, the latter two are infrared. Most of the optical transmitters in modern optical networks are semiconductor lasers [102].

3.2.1 Optical gain in semiconductor lasers

Three processes are vital to all lasers i.e. *absorption, spontaneous emission,* and *stimulated emission.* When a photon of energy E= $h\nu$ is incident on an electron with ground state energy level E_1, the photon gets absorbed into the electron raising its energy to excited state $E_2 = E_1 + h\nu$. This process is known as *absorption.* An electron cannot stay in the excited state for long period. After a particular time the electron reverts to the ground state energy emitting the photon of energy $h\nu$. The emission of photon by an atom without any external impetus is called spontaneous emission. According to Einstein's prediction '*if a photon can stimulate an atom to move from a lower energy level E_1 to a higher energy level E_2 by means of absorption transition, then a photon should also be able to stimulate an atom from the same upper level E_2 to a lower level E_1*' [58]. Hence an electron in an excited higher energy level E_2 when hit by an incident photon with energy $h\nu$, can emit a photon of energy $h\nu$, i.e. coherent with incident photon, and drop to lower energy level E_1, such that $E_1 = E_2 - h\nu$. This mechanism is known as stimulated emission.

If the net upward and downward transitions are equal, it is a state of thermal equilibrium in which spontaneous emission dominates and optical gain cannot be achieved [103]. In order to operate away from thermal equilibrium and to achieve population inversion through stimulated emission, the device is pumped with excessive photons or electrons. Semiconductor laser is electrically pumped by applying electric potential across a pn-junction [104]. The active medium in semiconductor lasers is based on pn-junction. A pn-junction is formed when p-type and n-type semiconductor materials are brought together. Figure 3-1 shows the p-n junction in thermal equilibrium (a, & c), and under forward bias situations (b & d).

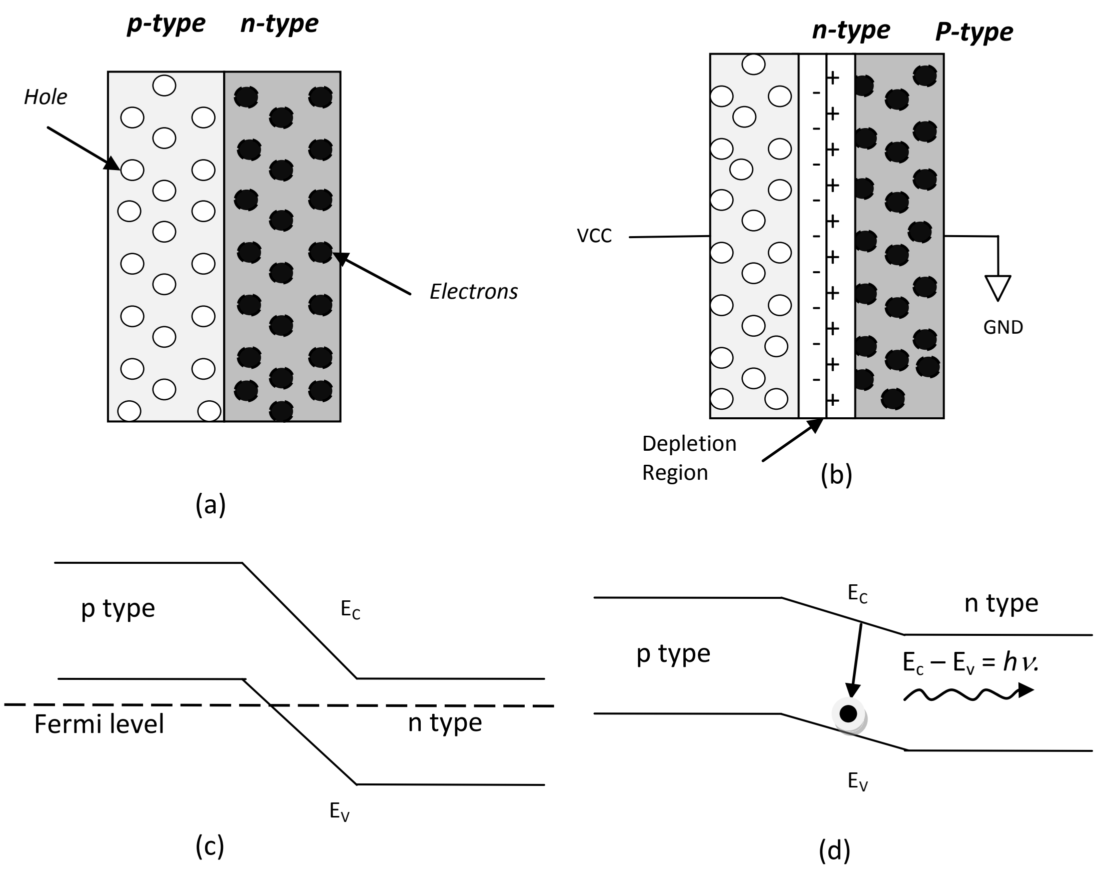


Figure 3-1: (a) PN Junction unbiased, (b) PN Junction forward biased, (c) PN Junction Conduction and Valence band energy profile – unbiased (d) PN Junction forward biased energy profile

In thermal equilibrium, there are no free electrons and holes due to their recombination. The depletion region electric field also prevents further carrier drift and diffusion into the intrinsic region [105]. When electrons and holes are injected, each from either side by applying electrical voltage, the junction becomes forward bias, and this field reduces, allowing the diffusion of electrons and holes into the depletion region where they can recombine and produce photons by stimulated or spontaneous emission.

3.2.2 Hetero-junction

Devices based on the PN junction shown in Figure 3-1 forms a homo-junction device. In this configuration the electrons and holes cannot be are not well confined and the carriers are free to recombine over a large region within the material resulting in decrease of carrier densities. Another assembly is Hetero-junction [106] in which a thin layer of another material with different band gap but same lattice constant is sandwiched with two layers of higher band gap material that increases the density of charge carriers by confining them in small region [107]. In doing so, the efficiency of the recombination process can be significantly improved. This thin layer in semiconductor laser-based devices is called the *active region*. The refractive indices of the materials are chosen in such a way that radiation is confined within this layer which acts like a waveguide [108]. This difference in band gap between the active layer and the surrounding substrate, serves to confine the carriers. Figure 3-2 shows a heterojunction scheme.

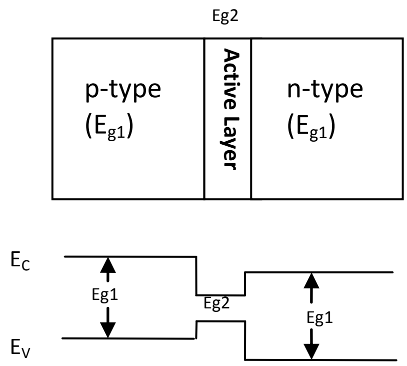


Figure 3-2: The schematic of a hetero junction

The wavelength of the emitted photons is related with the energy gap through the relation

$$E_g = E_c - E_v = h\nu = hc(1/\lambda_{PL})$$

Equation 3.1

Where λ_{PL} is the wavelength of emitted light, h is planks constant and c is the speed of light. A parabola model as depicted in Figure 3-3 for the energy levels of conduction and valence bands vs. the wave number k ($k = 2\pi/\lambda$) presents a better understanding of energy level distribution in the material.

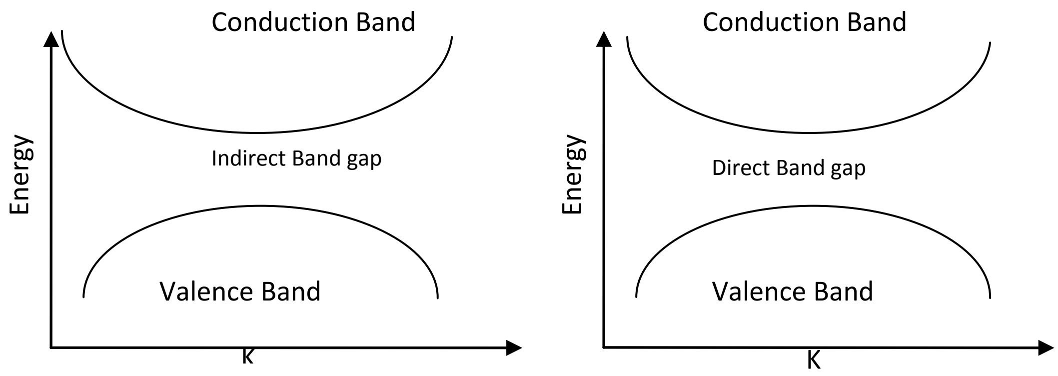


Figure 3-3: (a) Indirect band gap, (b) Direct band gap.

As it can be observed from the Figure 3-3, in a direct band gap material the minima of conduction band lies right above the maxima of valence band thus easing the transition at the respective wavelength, which is referred to as photo luminance wavelength of the material. The minimum energy gap of the active layer and thus the photo-luminance wavelength can be chosen by choosing any direct band gap material for active layer. For 1.55µm region materials such as $In_{1-x}Ga_xAs_yP_{1-y}$ and $In_{1-x}Ga_xAs$ are used. The composition decides the band gap and the wavelength, and therefore the photo luminance wavelength can be adjusted by selection of correct values of x and y.

3.2.3 Resonators

Semiconductor laser like other lasers have resonating mirrors that provide optical feedback. Traditionally there is a partial reflecting mirror on output end a full reflecting mirror is used on other side. The initial population of photons in laser is spontaneous emission. These photons then interact with other excited electrons for stimulated emission. To utilize the full capacity of the excited population of photons, the emitted photons are reflected back from the mirrors and result in greater amount of stimulated emissions thus amplifying the radiation to greater extent. When reflected back into the active layer these photons result in greater number of stimulated emissions.

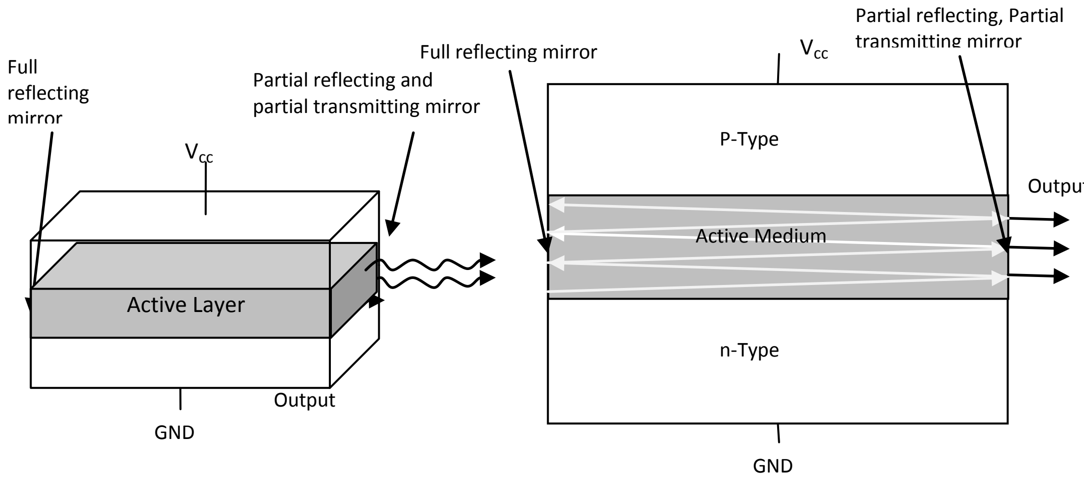


Figure 3-4: Structure of a semiconductor laser (not to scale), depiction of resonating mirrors.

The condition for oscillation of a wavelength in the laser cavity is

$$k\lambda = 2nL$$

Equation 3.2

Where k is an integer, λ is the wavelength of light, n is the effective refractive index of the guided mode and L is the length of the laser cavity.

The discussion on resonators is vital to our discussion, as the resonators form the basis of difference between lasers and optical amplifiers. An integral part of semiconductor lasers, the resonators or any resonating modes are undesirable for modern SOAs. This topic will be discussed in detail in following section on SOAs.

3.3 Semiconductor optical amplifier-SOA

3.3.1 Introduction

Semiconductor optical amplifiers-SOAs have been in use for a couple of decades in fiber optics for detection and amplification of optical signals. SOAs are optical amplifiers that use a semiconductor material to provide the gain medium. SOA is driven by electric current i.e. electrically pumped and is able to receive an optical signal, amplify and emit the amplified output.

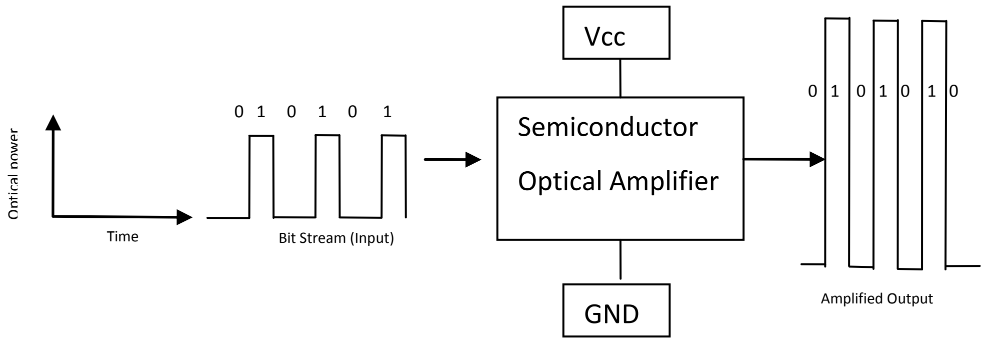


Figure 3-5: Depiction of working of a Basic Semiconductor Optical Amplifier

The output optical signal has roughly the same optical spectrum as that of the input signal but with higher intensity. The semiconductor optical amplifier is a small sized electrically pumped compact semiconductor chip with fiber connections. The gain bandwidth of the SOA is smaller. However SOAs can be designed for desired band of wavelengths. The amplification is normally polarization-sensitive, however many developments been made towards polarization in-sensitive SOAs. The issue is addressed further in section 3.5.1. The SOA can be easily designed for any band of wavelengths within the entire fiber transmission window. In addition, the support for high data rate and ability to integrate with other optical components, gives SOA a considerable edge over other counterparts, making SOA a high profile candidate for use as an optical amplifier for optical fiber systems [109].

3.3.2 Basic Structure of SOA

SOA is a variant of semiconductor laser. There are two main kinds of SOAs: Febry-Perot SOA or FP-SOA, and travelling wave SOA or TW-SOA. In FP-SOA high gain is achieved by resonating modes inside the cavity at resonant wavelengths. However, in TW-SOA resonance is undesirable; therefore there are no end mirrors. To enhance the travelling wave nature of SOA and to suppress any possible facet reflections, anti reflection measure like anti-reflection coatings, tilted waveguide and window region configurations are applied which can reduce end face reflection to as low as 0.001%. Since this creates a loss of power from the cavity which is greater than the gain it prevents the amplifier from reaching the lasing threshold and keeps it from acting as a laser

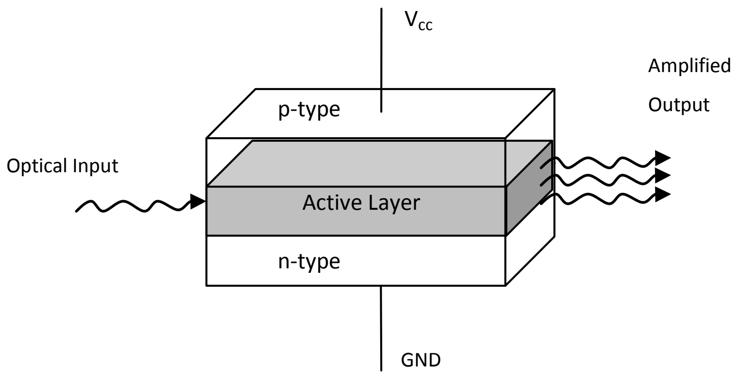


Figure 3-6: A Basic SOA structure with straight facet structure, a variant of semiconductor laser, with no mirrors. For the purpose of demonstration, no additional anti-reflection measure is shown.

Because the amplification medium and working of the SOA are the same as the lasing medium and the lasing process of the laser diode, the discussion of types of SOAs with respect to internal structure will be quite similar to that of the semiconductor laser.

3.3.3 Facet reflectivity

Initial generations of SOAs were Febry-Perot cavities or FP-SOAs, in which the gain is a strong function of resonant wavelengths and the reflections from the facets are significant. Elimination of mirrors for the purpose of travelling wave-TW SOA is not enough to suppress the resonating modes as the waveguide facets have a reflectivity of their own. In addition, the difference of refractive index between the active medium and the outer space also results in total internal reflections. Ideally the facet reflectivity of a TW-SOA should be zero. The non-zero reflectivity results in gain ripples (ΔG) expressed by the equation:

$$\Delta G = \left[\frac{1 + \sqrt{R_1 R_2}\, G_s}{1 - \sqrt{R_1 R_2}\, G_s}\right]^2$$

Equation 3.3

Here R_1 and R_2 are facet reflectivities and G_s is the single pass gain. For negligible facet reflectivities, the gain ripple is negligible thus smoothing the gain profile over the spectrum. However 100% transmittance is not practical. For practical TW-SOAs 3dB gain ripple is acceptable, as 3dB also defines the bandwidth of a transfer function.

To remedy this problem, anti-reflection coatings have traditionally been in use. An anti-reflection coating is a layer of transparent material that is annexed to the cross section of waveguide as a shield in front both of SOA opening. This is graphically shown in Figure 3-7 . The refractive index of this coating is less than that of the waveguide and greater than the outer space, normally air, so that any out coming light ray, if deviates from the axis, is refracted toward the perpendicular axis for maximum transmittance.

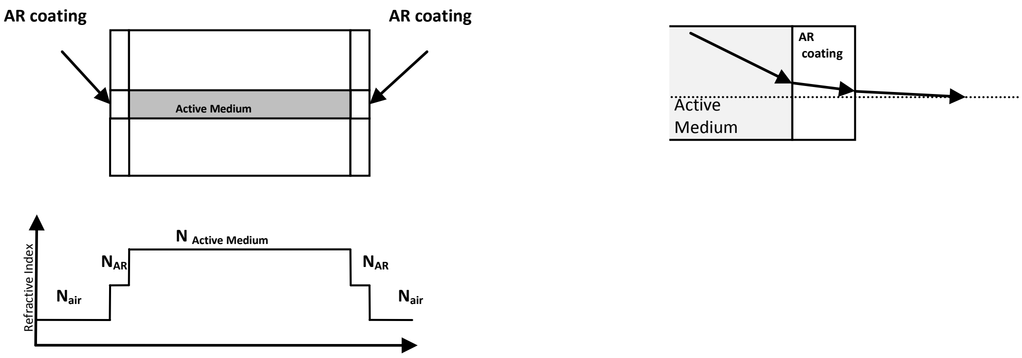


Figure 3-7: Demonstration of AR coating

Anti-reflection coatings are in use for a range of optical applications since 1950s [110]. SOAs however, to be the technology of choice for the vendors and to compete with other counterpart needs to decrease the manufacturing cost, where the anti-reflection coatings inflect additional overhead [42]. In this regard alternate anti-reflection measures like tapered facet and tilted waveguides have been suggested, some of which discussed in following sections.

3.3.4 Tilted waveguide and/or tapered edged SOA Structures

In an angled facet SOA, the active region is slanted away from the facet cleavage plane, thereby reducing the effective facet reflectivity. The relative reflectivity decreases as the facet angle increases [111]. However, the coupling efficiency between an SOA and optical fiber degrades at large facet angles due to the far field asymmetry. AR coating if used also becomes more polarization sensitive as the facet angle increases.

The tapered-end active-layer SOA have also been realized [112] for the purpose of polarization insensitivity, which is also another important pre-requisite for many applications.

Optimal facet-tilt-angles lie in the range between 7^{o} and 10^{o}. Increasing the facet tilt angle from 7^{0} to 10^{0} decreases the effective reflectivity from 10^{-4} to 10^{-5} [113].

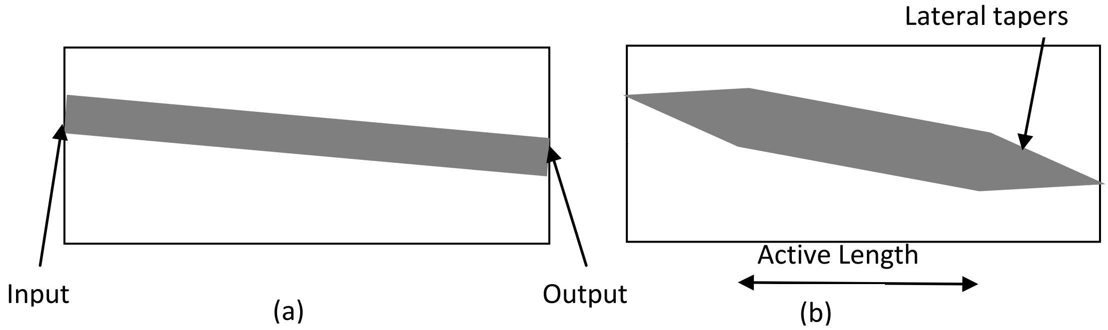


Figure 3-8: Angle Facet SOA - (a) Straight facets (b) Tapered Waveguide

3.3.5 Optical Gain

An optical amplifier increases the power of the optical signals passing through it. The ratio by which the input signal is increased is called Gain. Mathematically Gain is defined as

$$\mathbf{Gain} = \frac{\mathbf{Output\ Power}}{\mathbf{Input\ Power}}$$

Equation 3.4

And in decibels

$$\mathbf{Gain} = \mathbf{10log}\left(\frac{\mathbf{Output\ Power}}{\mathbf{Input\ Power}}\right)$$

Equation 3.5

As discussed SOA is an electrically pumped device with an optical input and optical output. The optical gain of the SOA as defined by Equation 3.4 and Equation 3.5 is the major transfer function of the device. The additional power for optical gain is provided by the injected electrons. These injected electrons result in increase of population of the high energy electrons leading to spontaneous and stimulated emission. While stimulated emission provides gain, the amplified spontaneous emissions-ASE is the main source of noise in SOAs.

A simple approach to the calculation of gain is through the considerations of carrier population in the active region. Assuming that there is no pumping and no stimulated emission, the decay in the instantaneous population density *'n'* of charge carriers can be explained by simple differential equation

$$\frac{dn}{dt} + \frac{1}{\tau_c} n = 0$$

Equation 3.6

Where τ_c is the carrier lifetime, that explains the spontaneous exponential decay in the population density. However the injection of carriers and photon emission is vital to the device. The rate of injection for injection current density ***'J'*** into the active layer of thickness *'d'* is '$\frac{J}{ed}$' where e is charge of an electron. Similarly the rate of change in population density of carriers due to stimulated emission of light intensity 'I' and frequency 'ν' equals $A_g(n - n_o)\frac{I}{h\upsilon}$) where n_0 is transparency carrier density, 'A_g' is differential gain, 'h' is Planck's constant, and 'Γ'is the active region confinement factor. The difference of rate of injected carrier density and the population inversion due to stimulated emission provides the forcing function for the inhomogeneous differential equation that describes the rate of change of instantaneous population density *'n'* of electrons of carrier lifetime inside the device as given by

$$\frac{dn}{dt} + \frac{1}{\tau_c} n = \frac{J}{ed} - A_g(n - n_o)\frac{I}{h\nu}$$

Equation 3.7

$$\frac{J}{ed} = \frac{dn}{dt} + \left[\frac{1}{\tau_c} n + \Gamma A_g (n - n_o)\frac{I}{h\nu}\right]$$

Equation 3.8

Equation 3.7 and Equation 3.8 are both the same however arranged differently. Equation 3.7 separates the natural response (L.H.S) and the forcing function (R.H.S). The arrangement in Equation 3.8 describes the division of injected carriers into two portions: carriers grounding due to the photo emissions and carriers increasing the carrier density.

Similarly the light of intensity 'I' travelling along x-axis inside the waveguide if the photon emission is assumed to be stopped, will undergo attenuation defined by the differential equation

$$\frac{dI}{dx} + \alpha I = 0$$

Equation 3.9

Here α is the waveguide loss-coefficient. As the stimulated reinforces the light intensity the rate equation becomes

$$\frac{dI}{dx} + \alpha I = \Gamma A_g (n - n_o) I$$

Equation 3.10

Solving the equation 3.5 for instantaneous population density *n, s*ubstituting in 3.7, and substituting for saturation intensity $I_s = h\nu/\tau_c A_g$ and gain coefficient $g_o = A_g = \left(\frac{\tau_c J}{ed} - n_o\right)$ we get

$$\frac{dI}{dx} = I\left[\frac{\Gamma g_o}{1 + \frac{I}{I_{sat}}} - \alpha I\right]$$

Equation 3.11

The small signal gain (I <<Is) can be calculated by integrating Equation 3.11 over the length of the amplifier:

$$G = \frac{P_{out}}{P_{in}} = e^{(\Gamma g_o - \alpha)L}$$

Equation 3.12

Here P_{OUT} and P_{in} are the signal powers at the output and the input of the device. From Equation 3.12 it can be deduced that the gain of the device can be increased by increasing the material gain g_o, device length and confinement factor and by decreasing the internal loss. However this only occurs up to a point and in practice the achievable SOA gain is limited not by any of these parameters but by the self saturation due to spontaneous emission.

3.3.6 Electrical pump and control

SOAs are electrically pumped devices. The SOA can be switched on and off at a very high speed, and thus can be used as electro-optic modulator as well for fast switching between packets. In addition to the fast on and off characteristic, the injection current can be varied thus varying the gain and/or lasing profile of the SOA at a very high speed. This property of the SOA has been used in the adjustable gain clamped SOA [114] for the purpose of gain clamping. However the dynamic runtime decision to adjust the current of the SOA based on the information received from the incoming burst or packet remains a problem, and achieving the ability to do so could be a possible solution, though not the only solution to the problem of equalization of bursts in burst switched network.

3.3.7 Polarization Sensitivity

An optical signal like all electromagnetic waves can be decomposed into transverse electric –TE and transverse magnetic - TM modes that are perpendicular to each other. These two modes are also perpendicular to axis of propagation along the length of the waveguide. In polarized signal one of the transverse modes lags behind.

Optical fiber which acts as the waveguide for optical signal transmission, normally faces bending, material imperfection and coupling effects, causing difference of refractive index ratio and confinement factor for perpendicular modes. This results in change of state of polarization for the optical signal. The state of polarization of a signal is normally not known, therefore most of the network devices, including optical amplifier have to be polarization insensitive.

Change in polarization of the signal is mostly because of the difference in confinement factors for TE and TM modes due to asymmetric cross-section of waveguide. Because it is not possible to generalize the state of polarization of a signal, the SOA if used to amplify the signal should be able to accept and amplify signal with any state of polarization.

SOAs are generally polarization sensitive and do not completely preserve the state of polarisation. There are a number of factors that affect the state of polarization of the signal while being amplified by the SOA. Before we briefly discuss these factors it is important to note that while some of the polarization disturbing factors are either intrinsic, unavoidable or system requirement, other factors are exploited to counteract their effects so that the overall polarization insensitivity could be achieved.

Generally the confinement factor for the TE mode is stronger than TM because the active region does not normally have the same refractive index profile on both sides of waveguide cross-section. An index difference of 10^{-4} [115] and TE and TM has been reported.

The inclusion of a separate confinement hetero structure –SCH can provide the control of the confinement factors ratio for TE and TM mode through varying the refractive index profiles Figure 3-9(c). SCH is a thin layer of a material slightly different to that of the active region. The material has a bandgap higher than that of active region and refractive index between those of active region and the surrounding substrate. The SCH can be used to maintain the confinement factors ratio by inclusion of SCH of different composition and thickness.

Using a perfect square cross section Figure 3-9(a) waveguide brings refractive index profiles closer thus decreasing the confinement factors' difference for TE and TM modes. The technique works very well. However etching the width of waveguide close to the required thickness is not easy especially in mass production.

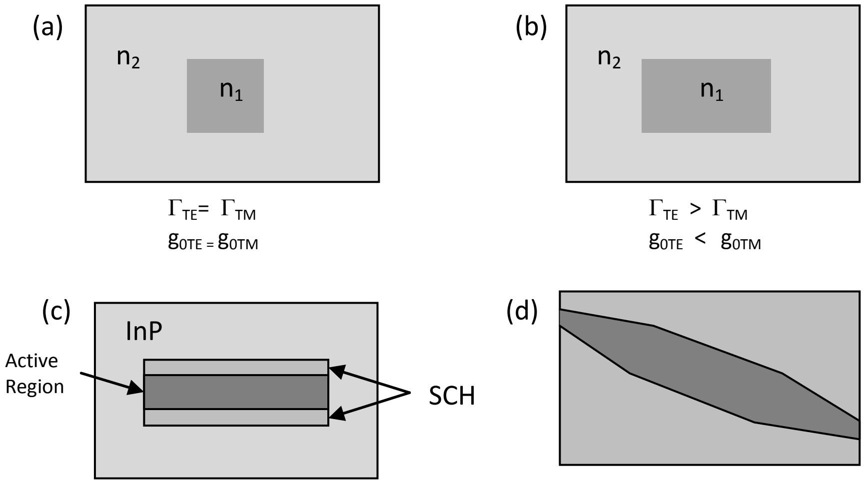


Figure 3-9: (a) Perfect square waveguide cross section (b) Strained active region (c) SCH included SOA (d) Tapered Edges active region

Courtesy C. Michie et el[112]

Alternatively straining of the active-region material is another technique to adjust the material gains for TE and TM polarizations as shown in Figure 3-9(b). Normally the active region and substrate have same lattice constants. However for growing strained layers a material composition is chosen so that its lattice constant is slightly different to that of the substrate [116]. Bulk layers grown with tensile strains increase the TM material gain relative to the TE material gain, which can balance the difference of confinement factors' effects.

Anti reflection coatings are also important issue with regards to polarization dependence of SOA. AR coatings are generally polarization dependent, and were considered the main cause of polarization dependence in early SOA devices. AR coatings help suppressing the resonating modes and so could not be avoided. However other anti-reflection techniques have been developed to either replace or accompany the AR coatings. Tilted waveguide and tapered edges are some of the solutions (Figure 3-9 (d)), discussed already in Section 3.3.4.

Chapter 4: Measurements and Analysis

4.1 Motivation for the research

In the context of upstream Burst Mode Extended GPON as discussed in Chapter 1, the data burst may be characterizeyuhbd by difference losses depending on the path from the end users and the type of system they are coming from. This puts a stringent requirement on the amplifier of being able to adjust the gain dynamically.

This issue has been a subject of research of many researchers during the last few decades, and many application-oriented solutions have been suggested [94, 117-121]. In this section we will discuss the qualification of SOA and the motivation for the research in the context of its application in prospective extended-GPONs.

As discussed in Section 2.6.3, an amplifier is required for the purpose of upstream burst mode traffic that can:

- Clamp the gain to a required level
- Take the information from the incoming burst and change the clamping level dynamically at the speed comparable to bursts speed.

To provide PON based optical access services more effectively, long reach (and high-splitting number) systems based on burst- mode optical amplifiers have been extensively studied [122] We are dealing with GPONs that currently operate at approx 2.5 Gb/s, and looking to 10/100 GB/s data speeds. EDFA has been a good choice for optical amplification. However in the scenario we have in front of us, the EDFA may not be the best candidate for a number of reasons. The upstream data in GPONs uses 1480nm, whereas the EDFA can only handle 1550nm wavelength. The 1550nm wavelength is currently in used by Cable TV networks and there can raise legal issues. Fiber Amplifiers made up of other rare earth elements, e.g. Thulium [123], Praseodymium [124] and Ytterbium [125] have also been fabricated and they can handle other wavelengths. Thulium doped fiber amplifier with gain peak at 1470nm is suitable to be used for S-band. However it provides small signal gain of 25dB at 1470nm which is very low. In addition the availability of suitable rare earth metals also constraints the use of these doped fibers. An amplifier is required that either has a wide spectrum support to cover the required wavelength or has the ability to be designed for a specific wavelength at low cost.

An EDFA can handle and amplify any data rate. However the gain saturation and recovery has a characteristic time in milliseconds range, whereas the full length of a

GPON upstream frame is normally 125µs, i.e. smaller than the recovery time. An EDFA normally operates in saturated mode with constant output power [126]. In burst switching, variable size bursts from different sources can require different gain levels. If the speed of the data is on the order of giga bit per second, then the gain recovery might be required on the scale of nano second level. For single stream of signal where there is not much variation in the signal power, the EDFA works fine. However, because of gain recovery time of the order of milliseconds EDFA becomes completely unsuitable for data bursts or high speed especially Gigabit traffic.

The SOA normally works in linear region and has a gain recovery time at the order of nano seconds, as shown in Figure 4-1. This gain recovery in SOA is much faster than the 10 Gb/s data rates. This gives SOA enough time to get adjusted between the bursts.

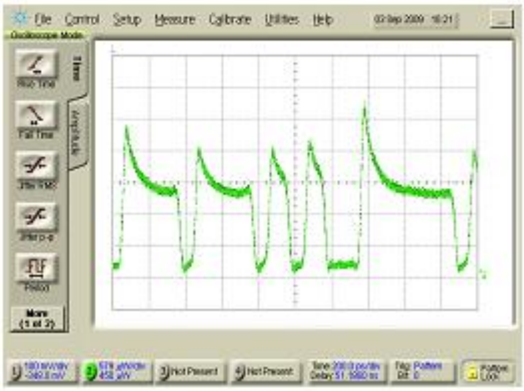


Figure 4-1: High speed gain recovery in SOA (Time vs SOA output power, Scale x-axis: 200ps per div, y-axis: 579µW per div) :

SOA on the other hand has a very high gain recovery rate, which can be observed from the results presented in this thesis. Furthermore, the SOA does not treat the multiplexed wavelengths separately i.e. for WDM networks, the sum of all the WDM channels will decide whether SOA will be in linear or the saturation region. SOA can be designed and fabricated for any wavelength by altering the composition of materials used as active medium. Alternatives to AR coatings have made SOA more robust and inexpensive than before. Therefore, there is reasonable evidence of suitability of SOA for use as amplifier for burst mode receiver in GPONs. We chose SOA for experimentation and analysis in this research work.

SOA however has its own operational limitations in the amplification process with regards to gain saturation and dynamic range that need to be addressed. These limitations and constraints are discussed in detail in this chapter and Chapter 5.

SOA can be used as a simple inline amplifier in the small signal region, where the linear gain remains stable while varying the input signal power. Though highly desired, the linear behaviour of small signal region is not available above a certain value of signal power called saturation power. As the signal power increases further beyond the saturation power, the gain decreases more rapidly.

Operating the SOA in the saturation region can cause inter-symbol interference-ISI [127] or patterning because the recovery time the SOA is normally in a range comparable to the data modulation rates. Therefore to use the SOA in linear region, it becomes necessary to ensure that the overall signal power going into the SOA does not exceed the saturation power and thus keep the SOA from driving into saturation.

In the light of the discussion, we have come to the conclusion to select SOA for testing to be used as in-line optical amplifier for Burst mode WDM-GPONs, based on the merits of SOA. However a number of issues regarding the performance were also discussed that need to sorted out. A number of suggestions and ideas on as to how the issues can be addressed have been put forward. However before going any further and testing new arrangement, it is necessary to understand the behaviour and characteristics of the basic SOA. This chapter is based on the measurements taken on the SOA, analysis and conclusions. Measurements were taken on a commercial SOA and the results were plotted and discussed. The measurements form the basis of theoretical understanding, and make a road map for the further investigations into the applications of the device, as per the network's requirements.

The remaining chapters comprise of measurements, discussion and analysis of SOA in order that it can address the problem and an effort has been made to explore the faculties of the device. Several aspects like error analysis, losses in Power penalties in SOAs is discussed in details.

4.2 Parametric measurements on optically amplified system using SOA

Figure 4-2 shows the experimental setup used to perform the basic parametric measurements on SOA. The apparatus include a tuneable laser, an optical attenuator, an SOA, a polarization controller, an optical Isolator, an optical spectrum analyzer-OSA, computer controlled SOA-current driver, Power supply, PC, and Fiber probes with cross/straight connections.

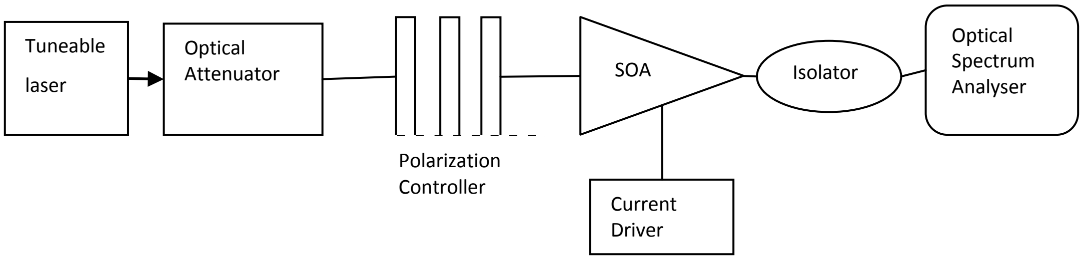


Figure 4-2: Block diagram of experimental setup for parametric measurements on an SOA.

The analytical quantities that were used/measured and/or calculated and plotted during this analysis are:

- Input power (dBm)
- Output power (dBm)
- Gain (dB) = Output power – Input power
- Drive current of the SOA (mA)
- Wavelength of the optical signal (nm)

Based on the measurements taken on the device according to the setup shown in Figure 4-2, different graphs were obtained in order to study the response of the SOA to changing parameters. Following is the summary of the observations and results from these experiments.

4.2.1 Output Power Vs Gain: Case of saturation

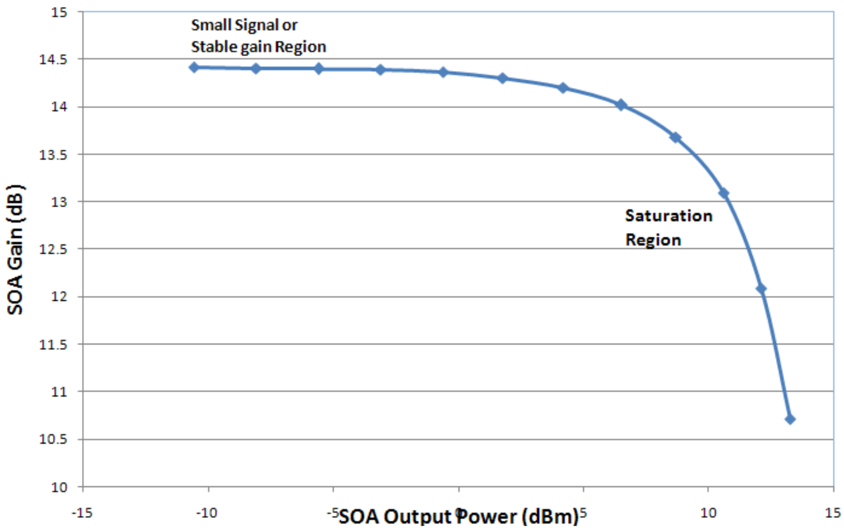


Figure 4-3: When operated at a power higher than level the gain decreases; the behaviour of a typical SOA.

As we can see from the Figure 4-3 , the gain of the SOA for a specific injection current is almost constant over a span of output power, but above a certain output power, the gain start to decrease rapidly, thus indicating saturation in the device. The constant gain observed on the left hand side of the gain curve is known as small signal gain. It can be concluded from the curve that for linear amplification, the SOA can be used only for a range of signal power limited by the saturation power. Beyond the saturation power barrier, the gain starts to decrease. This decrease in the optical gain at higher output powers is due to the depletion of carriers inside the active region [109].

4.2.2 Drive Current and the Gain of SOA

Figure 4-4 shows a set of plots for gain response to the output power for 1550nm wavelength, at twelve different drive currents, ranging from 16.7mA to 286mA.

Figure 4-5 shows an increase in gain with respect to change in drive current. However the set of plots also shows that with increase in current the effect of current on gain decreases. For instance we can see that by changing current from 25mA to 50mA, the gain jumps from 3dB to approximately 13dB, i.e. 10dB change.

On the other hand, at higher currents even for a 50mA increase in current there is hardly 1dB increase in gain. This depicts the gain saturation with respect to the drive current.

The increased number of charge carriers increases the opportunity for stimulated emissions which increase the gain with increase in injection current. However decrease in the gradient of increasing gain with current is mainly due to increased auger recombination and increased ASE.

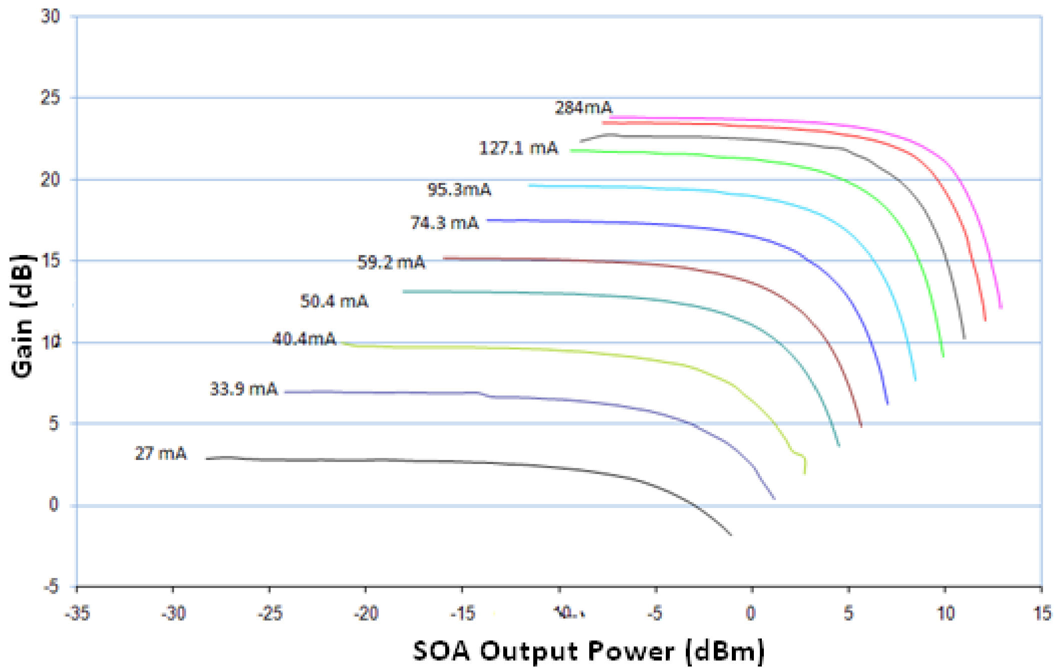


Figure 4-4: Plots showing optical gain Vs output power of SOA for different drive Currents. (measurements on a typical commercial SOA)

The recombination mechanism is proportional to the cube (n^3) of the carrier density and thus becomes dominant at higher injection currents. Thermal heating due to increase of charge carriers might also affect the gain as this causes leakage of carriers from the active region.

Another important observation that can be made from Figure 4-4 is change in saturation power with the change in drive current. The gain as discussed above could be increased and increase by varying the injection current. However by decreasing the gain also decreases the saturation power and vice versa. This variation in saturation power is one of the major issues in employment of SOA in optical networks. The gain of the SOA cannot be controlled independently of saturation power, and further investigation into this behaviour is done in the following sections.

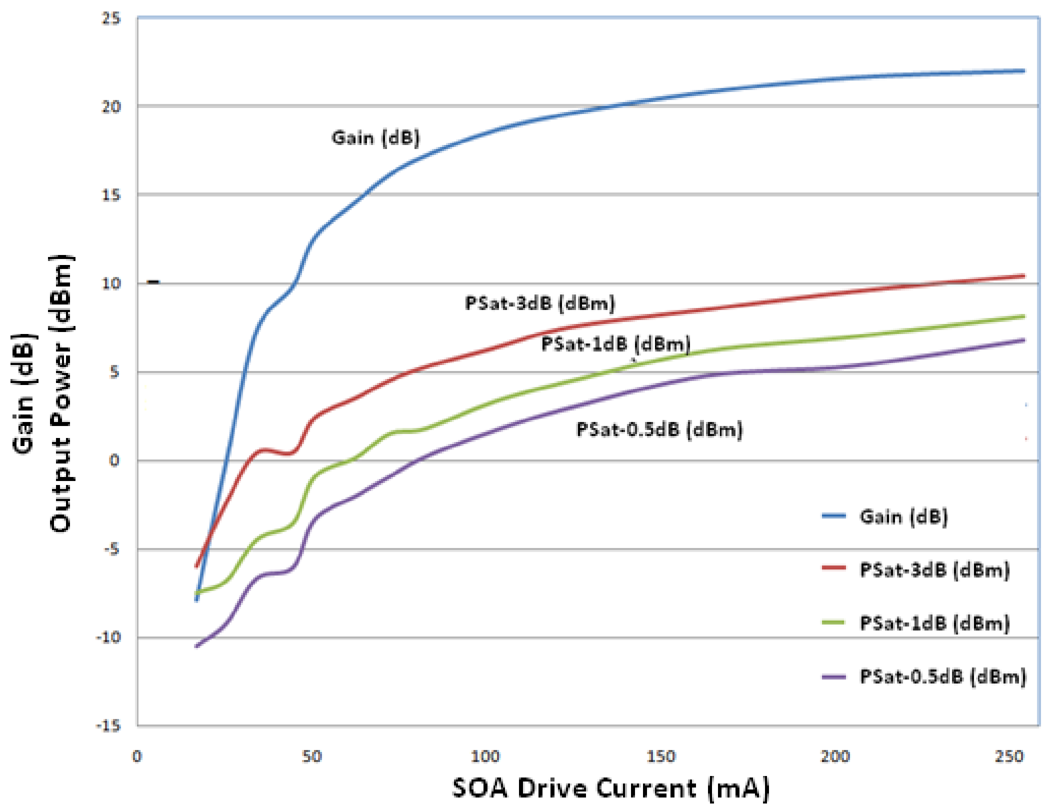


Figure 4-5: Drive Current of SOA Vs the Gain and Saturation Power

The P_{SAT} and Gain response to drive current is pictured in detail in Figure 4-5. The figure shows the relationship between the drive current and the gain of the SOA, and between the drive current and the saturation power.

The Figure 4-6 shows a relation between the small signal gain and the saturation power. From the graph we can see that the saturation power is also increasing as we increase the gain. In other words, a constant saturation power is not available for varying gain values. This results in higher power deprived of small gains, as the small gain curves saturate before reaching high power.

For example let us consider the case where we are controlling the gain to get 5dBm output power. It can be acquired if approximately 17dB or higher gain is required. If a lesser gain is required to get the same output i.e. 5dB, the SOA will have to be operated at lesser gain. However if the SOA's small gain is decreased by decreasing the drive current, 5dBm POUT will be in saturation region.

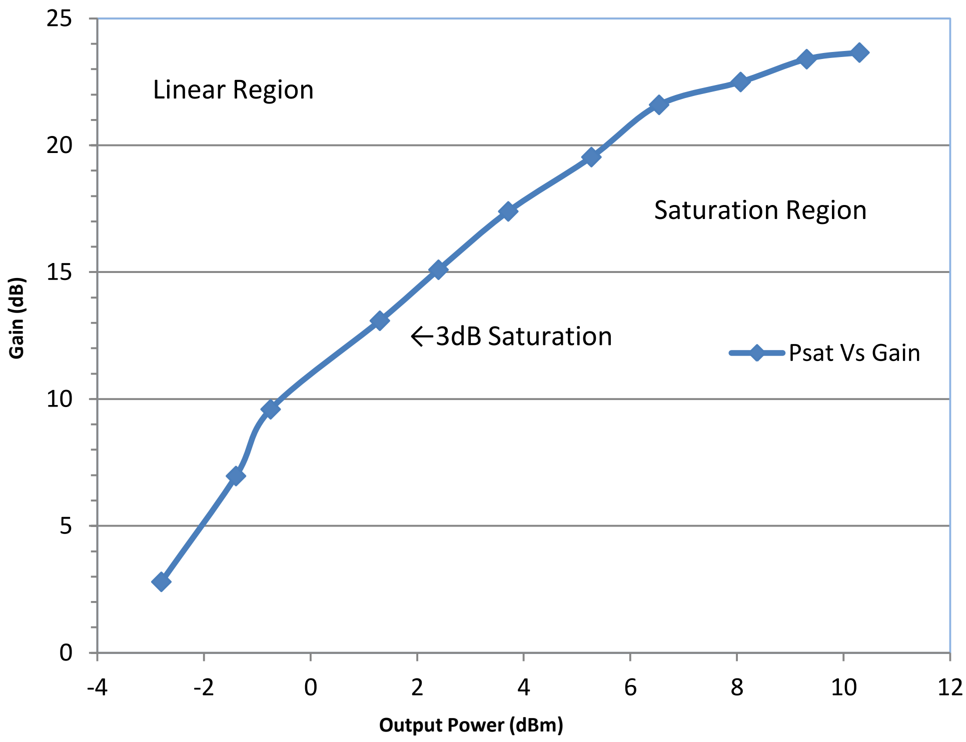


Figure 4-6: Saturation power vs. Gain

This analysis also gives rise to the consideration of maximum input power for a specific gain and/or drive current. The input power analysis is discussed in detail in the discussion on commercial SOA in coming section.

In Figure 4-5 both gain and P_{SAT} are plotted against drive current on the same graph that gives us the amount of maximum small signal gain available at which the P_{SAT} ceases to increase with current. In addition we can see that gradient of P_{SAT} begins to drop at drive current lower than that of fall of gain. However the rate of drop of P_{SAT} is almost the same as the decrease in gain. This phenomenon is clearer in Figure 4-6 in which Gain vs. P_{SAT} is drawn. Gain and P_{SAT} seem to be proportional to each other. The plot reinforces the presumption that high output power but with small gain cannot easily be achieved with the device.

Traditionally 3dB decrease in gain is considered as saturation point that is used as *consistent point of comparison for different device.* However the actual saturation point is decided by loss in gain that the system can tolerate. Some optical communication systems do not tolerate 3dB saturation level, as this can result in crosstalk between signals due to cross gain modulation. For such systems 1dB decrease in small signal gain is considered the ceiling of linear regime. In wavelength switched networks where the average gain saturation and number of channels and/or users are interconnected, the gain may be required to remain as close as 0.5 dB to small signal gain [128]. However the function and shape of the curves and behavior is almost similar for 3dB, 1dB and 0.5dB saturation level. Therefore investigation on one of these points leads to a suitable conclusion that can be generalized. For the purpose of this thesis we will be considering 1dB saturation limit, most of the time. We will observe and verify our selection in error rate measurements in Chapter 5 as well.

As discussed in Chapter 3, P_{SAT} is directly proportional to I_s, and I_s can be increased by decreasing carrier life time i.e increasing the carrier density. Therefore increase in saturation power can be explained by the increase in carriers' density (or bias current).

4.3 Measurements and analysis of different commercial SOAs

4.3.1 Measured devices

In order to study the effect of design and dimension of SOA on its performance and behavior we have taken measurements on four different SOA and their analysis is presented in this chapter. The purpose of these measurements is to study and analyze the role of design parameters of SOA in performance evaluation and response to variety of conditions.

The structure of the four SOAs are given in [112]

Device ID	Length Active region	λ_{PL} Photoluminance Wavelength	comments
021934 (SC-15-0089-677&678-C603155)	600um	1.55μm	PL shift towards blue by 40nm
021909(SC-15-0089-560&561-C602142)	600um	1.55μm	• Same as 021934 with different AR Coating • PL shift towards blue by 40nm
021923(SC-15-2015-2819&2820-B101133)	1000um	1.59μm	Standard design for Gain peak 1550μm
021256 (SC-15-0125-600&601-B603054)	600um	1.59μm	Standard design for gain peak at 1550μm

Figure 4-7: Table of detail specifications of SOAs used in measurements.

4.3.2 Pout Vs Gain – Analysis and comparison of the SOAs

Let us start with the basic P_{out} Vs Gain curves, as shown in Figure 4-8. The figure shows the P_{out} Vs Gain for the three devices 21923, 21256 and 21909. Three sets of measurements were taken for each device at probe wavelengths of 1524nm, 1550nm, and 1563nm. The bias current for all the devices was kept constant at 200mA for comparative analysis. The device 21934 has not been included in the figure as the device's structure is same as 21909 with different anti-reflection coating and thus has behaviour very close to 21909 which results in overlapping and congestion in the graphs, making it difficult to read.

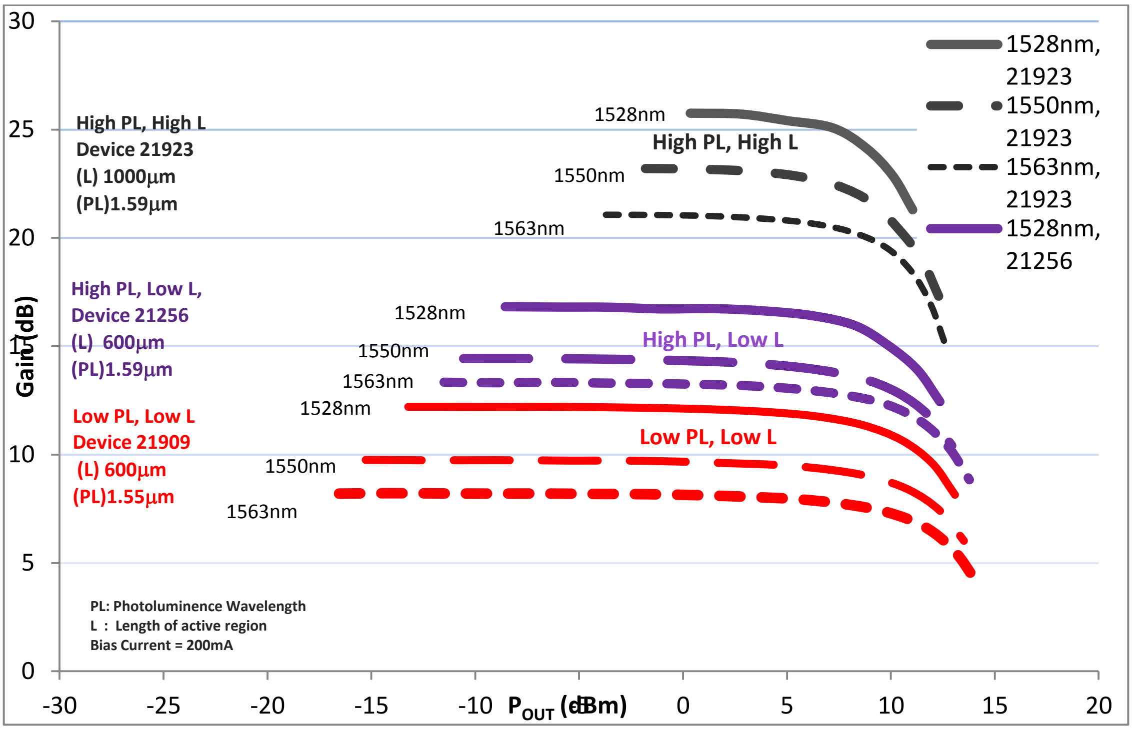


Figure 4-8: P_{OUT} Vs Gain of three SOAs. Colour used is black for 21923, purple for 21256 and red for 21909. Thick solid lines are response to 1528nm, long dashes for 1550nm and small dashed line for 1563 nm signal. Response to device 21934 is not drawn to avoid confusion because its plots are very close to plots of 21909.

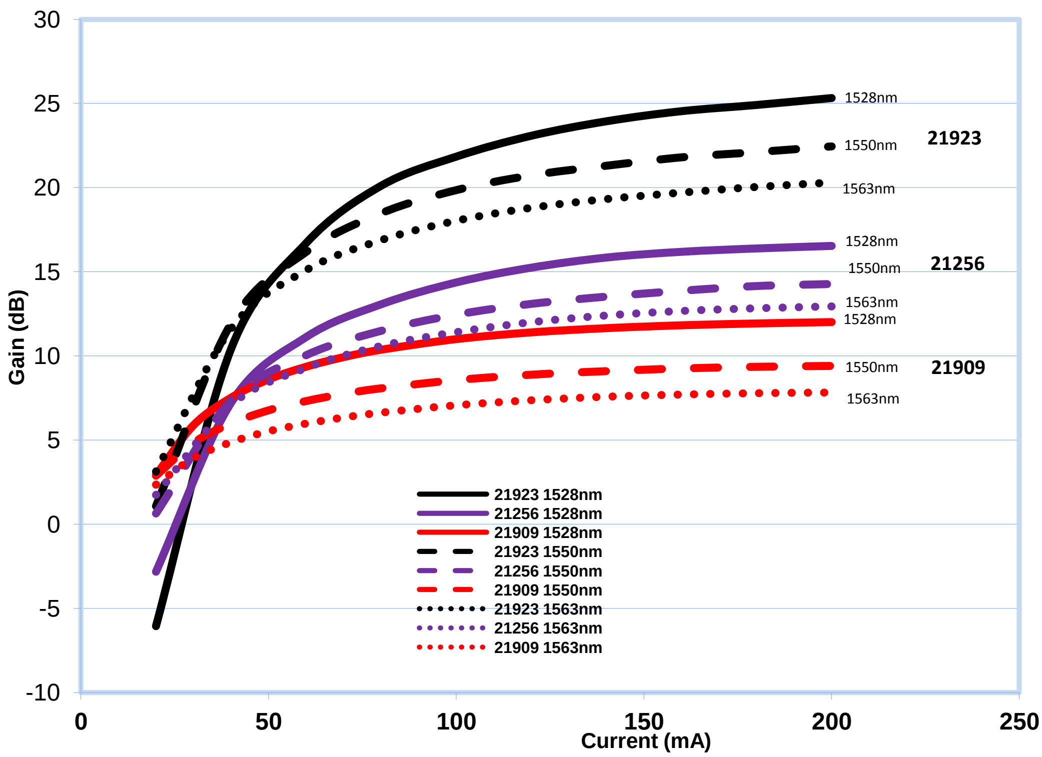


Figure 4-9: Current Vs Gain: different devices' response at various signal wavelengths for various devices.

The plots in Figure 4-8 and Figure 4-9 show a clear trend in the behavior. The few parameters that affect the gain of the devices are:

- Length of the active region
- Photo-luminance wavelength (PL) of the device
- Signal Wavelength

Active region length: It can be observed that longer active region result in higher gain. The device 21923 with 1000μm active region length and 1.59nm PL wavelength has highest gain. The device 21256 that has PL wavelength same as 21923 but shorter active region length (600μm) has 9dB less gain at similar signal wavelength. Longer active region provides greater opportunities of stimulated emissions as the photons (incident as well as emitted) travel along the length of SOA and collide with greater number of electrons. Therefore this device provides higher gain than its counterparts with shorter active region. It was discussed in Chapter 3 that gain of the SOA is directly proportional to the length of the active region. The point is verified by the plots in Figure 4-9 that show that at any particular injection current the gain is higher for longer devices and vice versa.

Photo-luminance wavelength: Photo-luminance wavelength λ_{PL} of the SOA, as discussed in Chapter 3, is the wavelength that corresponds to the bandgap E_g of the active region and is also the energy of the photon with wavelength λ_{PL}. E_g and λ_{PL} related by the equation

$$E_g = h\nu_{PL} = hc\,(1/\lambda_{PL}) = hc(\lambda_{PL})^{-1}$$

Equation 4.1

Where h and c are planks' constant and speed of light respectively and are constants; ν_{PL} and λ_{PL} are the photo luminance frequency and wavelength respectively for the material.

The Equation 4.1 tells us that a device fabricated for high Photoluminance wavelength has low energy gap i.e. the valence band and the conduction band will be very close to each other. Such a device when operated at wavelength smaller than λ_{PL} will yield high output power or high gain as shorter wavelength corresponds to higher energy. Therefore the gain peak of an SOA normally occurs at a wavelength below or blue shifted from λ_{PL}..

The devices 21256 and 21909 are of the same active region length. However λ_{PL} for 21256 is 1590nm and for device 21909 is 1550nm. For device 21256 having longer λ_{PL} has relatively smaller band gap thus easing electrons transitions with greater number of emitted photons. Therefore device 21256 despite of having same active region length, has greater gain at any signal wavelength as compared to device 21909.

Signal Wavelength: The measurements are taken on all the devices are taken at three wavelengths i.e. 1528nm, 1550nm and 1563nm. The response of all the devices to the signal wavelength is similar i.e. the gain was highest at 1528nm and lowest at 1563nm. Again we see that shorter signal wavelengths acquire greater gain and vice versa. One reason for this behavior is the relationship between wavelength and the energy of the photon as discussed. However, gain or output power of an SOA is not simply a consideration of the energy of individual photon, the major contribution to high gain is the increased population of photons emitted. The parabola model of band structure as discussed in Chapter 3 provides the explanation. At λ_{PL} the device has a direct band gap which is sharp and less number of carriers can be accommodated at bandgap. However greater number of charge carriers is available with higher energies inside the conduction band. Therefore, operating the device at a smaller signal wavelength results in greater number of transitions and thus, greater number of emitted photons.

Another observation that can be made from the Figure 4-8 is the increase in P_{SAT} with the increase in signal wavelength. The P_{SAT} for 1528nm for the device 21923 is around 10dBm whereas for the same device when injected with same drive current but at high wavelength exhibits P_{SAT} values of 11dBm for 1550nm and 11.3dB for 1563nm signal wavelength. This is because the higher signal wavelengths have lower gain output and for a specific carrier density saturate at comparatively higher power.

Coupling efficiency and packaging: The device 21934 is the fourth type of SOA that was used for these measurements. 21934 and 21909 are similar devices with same active region length and PL but with slightly different AR coatings and packaging, which in turn results in a small difference in the coupling efficiency.

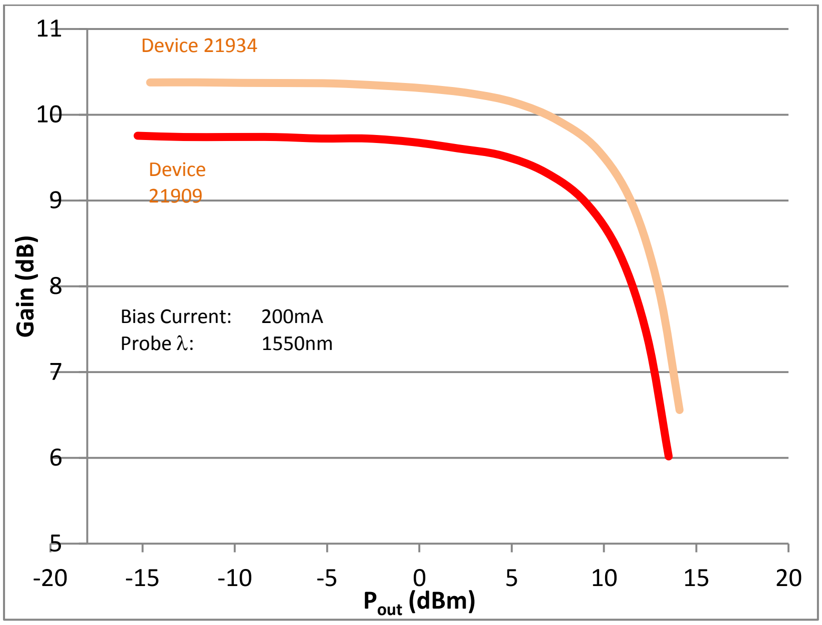


Figure 4-10: P_{OUT} Vs Gain curves of two SOAs with same Active Region Length and Photoluminance wavelengths, but different facet reflectivity.

It can be observed from Figure 4-10 that the device 21934 has approximately 1dB higher gain than 21909. This might be because of difference of finishing of end faces. Anyway 1dB gain difference is significant.

Polarization sensitivity: Polarization sensitivity is another aspect of the SOA. Figure 4-11 shows output power vs gain curves for 3 devices with each device measured for input source at maximum and minimum polarization. From the figure, it can be seen that varying the polarization of the probe varies the gain by a small but observable amount.

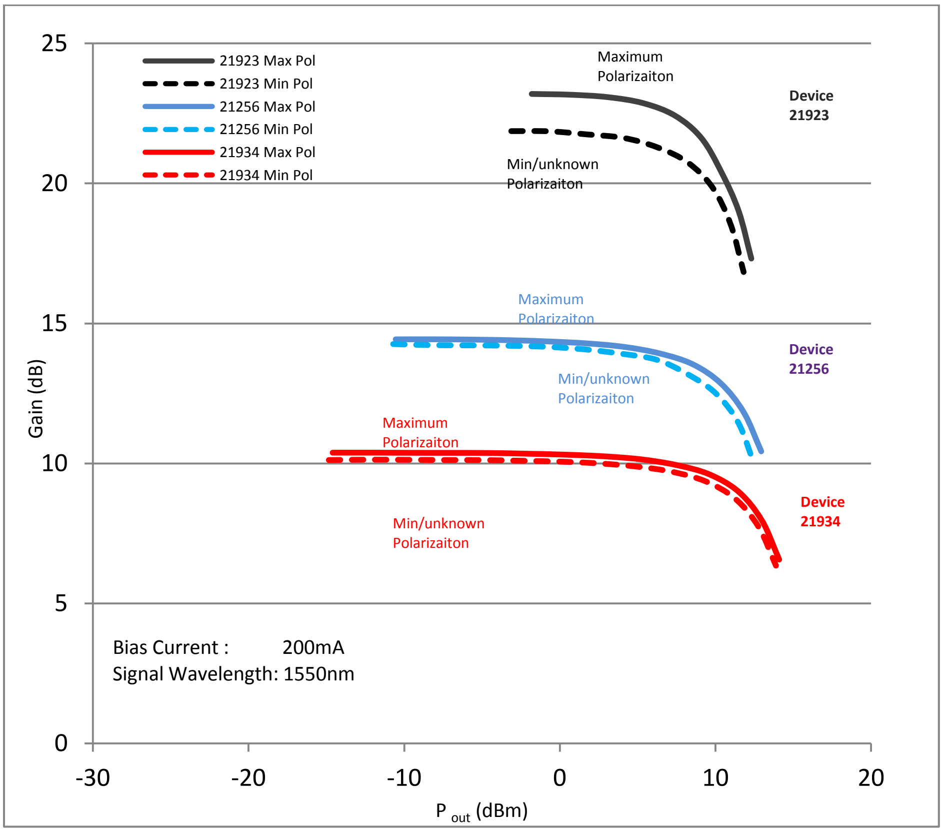


Figure 4-11: Pout Vs Gain for three devices – minimum/unknown and maximum polarization response illustrated.

As mentioned earlier, the devices we have used for these measurements have the polarization insensitive design as discussed in Section 3.3.7 and presented by [112]. That is the main reason the devices show little impact of polarization on gain, with the 21923 undergoing a maximum gain variation of about 1.2dB with change in the polarization of input signal.

4.3.3 Input power range for different SOAs

We can see devices have a variety of behavior with regards to input saturation profile - and gain. From Figure 4-7 through 4-9, we can deduce that different devices offer different gain levels but the output saturation powers are somewhat comparable. A better way to analyze the range of operation of the device is study the range of device's input power range. Here we can introduce input saturation power - P_{inSAT} defined as the minimum input power of the SOA at which the gain is 3dB less than the small signal gain. P_{inSAT} refers to same operational point as P_{outSAT}. P_{inSAT} is related with P_{outSAT} by

$$P_{inSAT} = P_{outSAT} - Gain_{dB\ (SAT)}$$

Equation 4.2

Where $Gain_{dB\ (SAT)}$ is the gain at saturation point and is 3dB less than the small signal gain.

However in this research work we are more interested in 1dB saturation as discussed in previous section. Therefore in the remaining discussion we will use P_{inSAT} instead of $P_{inSAT\ (1dB)}$, defined as the input power at which the gain is 1dB less than small signal gain.

P_{inSAT} plotted against the drive current is shown in Figure 4-12 . It can be observed that the devices 21909 and 21934 have higher input saturation power as compared to other two devices. However the response of these two devices to drive current is not constant and the P_{inSAT} changes with the increase in drive current.

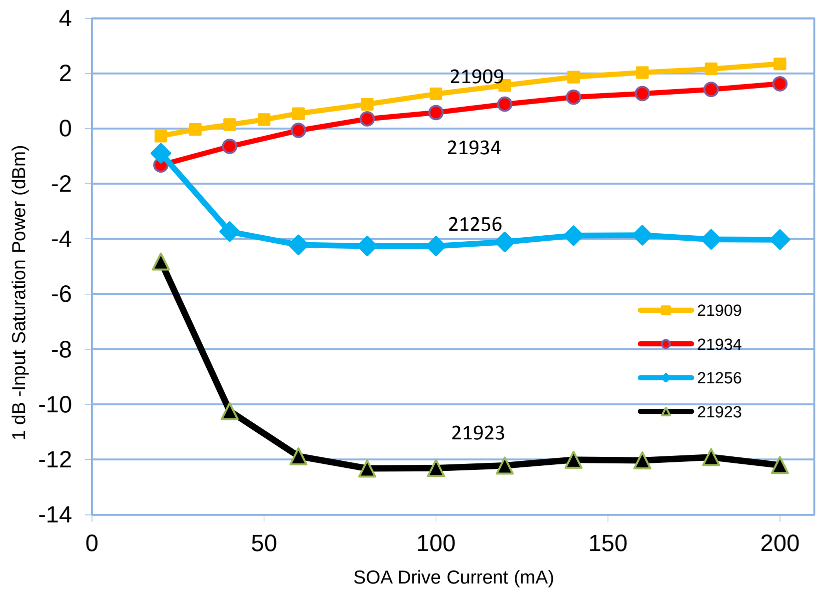


Figure 4-12: 1dB Input Saturation Power profile for 4 different SOAs

On the other hand the P_{inSAT} for devices 21256 and 21923 is -4 and -12dBm respectively which is very low but stable and does not change with drive current.

The device 21923 has the lowest input saturation power among the four devices, as it works below -12 dBm, which is very low. The device 21956 has comparatively higher values of input saturation power, i.e. approx -4dBm.

The other two devices 21909 & 21934 have high P_{inSAT} power i.e. between 4dBm and 8dBm. High P_{inSAT} power is a required feature and the two devices have this feature. However in contrast to the other two devices, we can see that the input saturation power is not constant over the range and is rising with the gain and this is not always desirable.

From Figure 4-12 we can conclude that for high gain devices 21256 and 21923, the P_{inSAT} can be kept stable while varying the gain as gain is controlled by injected current. However Figure 4-13 suggests that the gain is not exactly proportional to current and has a saturating behaviour. In order to investigate the true response of the device's P_{inSAT} towards variation in gain, gain vs P_{inSAT} is plotted in Figure 4-14.

The plots in Figure 4-14 display the saturation characteristics from a different perspective. Both the low gain devices have almost same P_{inSAT} response to gain as current. However in both high gain devices the P_{inSAT} decrease with increase in gain upto a certain level. For device 21256 the P_{inSAT} decrease until approximately 7dB gain and become stable above this value. The device 21923, which is the highest gain and lowest P_{inSAT} device of all considered, the drop in P_{inSAT} is greater as the P_{inSAT} decreases with increase in gain up to approximately 17dB and then becomes stable above this value.

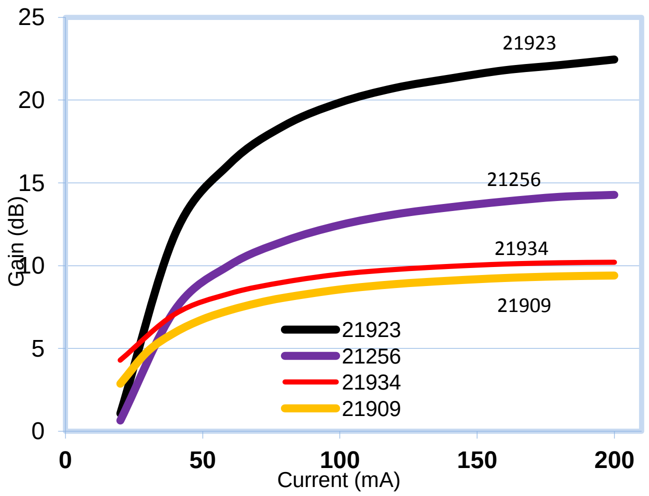


Figure 4-13: Gain Vs current – All four SOAs.

However if we look closely at the injection current and gain values above which the P_{inSAT} becomes stable are 50mA and 15db respectively for 21923. The gain control with constant P_{inSAT} above 50mA will be limited to gain values between 15dB and 25 dB approximately. If this is the required region of operation, then device i.e. 21923 is more useful than others.

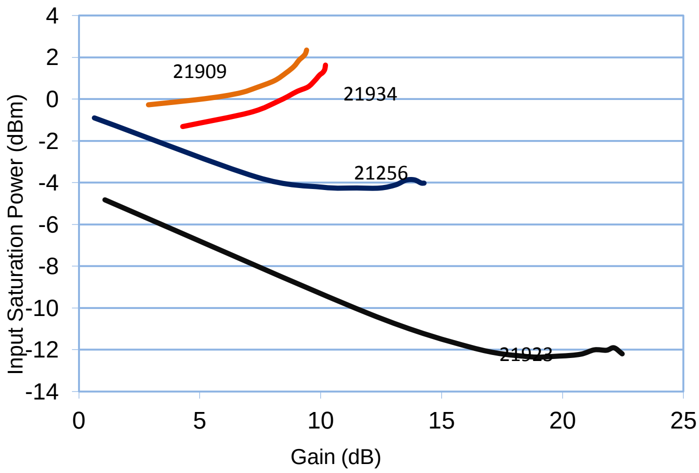


Figure 4-14: Comparison of Gain and Input saturation power(1 dB saturation) relationship for the 4 SOAs

Figure 4-12 gives a perception that the high gain devices with stable P_{inSAT} e.g. 21923 can be operated over a large range of injection currents. However plotting gain vs P_{inSAT} i.e. Figure 4-14 *(black color trace)* tells that despite of the large range of current values the device can be operated over a very short range of gain values. The point is reinforced by the current vs gain plot in Figure 4-13, which shows that the device in gain saturation with respect to injection current from 50mA to 200mA.

The behaviour of the device regarding the input saturation characteristics can be explained by considering gain response of the devices to bias current as shown in figure 4-9. The device 21923 has a maximum of 20dB gain which is highest. The device 21256 has approximately 14dB small signal gain. The devices 21909 and 21934 with high Pin-sat have small signal gain very low gain whereas the devices 21256 and 21923 have high and medium gain respectively. Looking into the input saturation characteristics of the four devices discussed above it looks like a trade-off between high input saturation power and high gains.

A high gain device when compared to a low gain device either has a longer active region or smaller bandgap or both. Both of these parameters result in utilization of greater proportion of available charge carriers. That is why there is high gain even at low input power. However for the same reason of rate of emissions the same device will have low P_{inSAT} at any specific current.

We have also discussed that P_{inSAT} of the high device does not increase with increasing the injection current (or the number of charge carriers). This is because the high gain device is designed in a way that a low power optical beam is able to utilize greater potential of the device. Therefore, injection of additional carriers, though increase the gain, do not increase the P_{inSAT}.

The device 21256 which is a medium gain device, has same PL wavelength as the device 21923 but has shorter active region. Because of shorter active region single-pass gain is less than longer device. However high power beam would have greater single pass utilization there this device has higher P_{inSAT}. The P_{inSAT} remains stable at -4dBm for gain values between 7dB and 15dB. It means that the gain can be varied within this range at constant P_{inSAT}. without changing the P_{inSAT} of the device.

The two low gain devices 21909 and 21934 have short active region(600µm) and higher band gap. As a beam of light has little utilization of available charge carriers in this scenario, device has higher P_{inSAT} at any specification current as compared to high gain devices. Moreover, the P_{inSAT} increases with the increase in injection current as the portion of charge carriers available for radiative recombinations increases.

4.4 Summary and conclusions

The chapter provides analysis of the parametric measurements on SOA. The chapter began with brief description of the experimental setup used for measurement. After that the basic parameters like gain, saturation power and injection current are discussed with regards to the measurement taken on a commercial SOA chosen randomly. During these measurement it was found that any specific injection current the SOA can handle optical power only up to a limit called saturation power; using the SOA above saturation power the optical decreases.

The gain of the SOA can be adjusted by adjusting the drive current. The effective dynamic gain adjustment through current is limited by reduction in the saturation power.

Changing the drive current of the SOA, also changes the saturation power of the SOA. A strong signal cannot be amplified by SOA for a small gain. The adjustment of the gain through drive current is effective over very limited dynamic range and hence demand of being able to provide a gain with large dynamic range for a large signal power dynamic range are the characteristics of the amplifier are to be employed for power equalization of the packets' optical power.

To study this problem in detail, we took parametric measurements on four different commercial SOAs. The design parameters that differentiated the devices were the photoluminance wavelength -λ_{PL}, length of active region and the quality of AR coating.

The summary of conclusions from measurement on these four devices is present in the following points:

- Length of active region is directly proportional to device gain.
- High λ_{PL} device has higher gain as energy gap is lower.
- Gain of device is inversely proportional to signal wavelength when operated within the spectrum of the device.
- Better AR coating enhances the gain. However we cannot relate the gain to the quality of AR coating at this as we do not have the correct figures to analyse from this perspective
- The high gain and medium devices offer a region of operation where P_{inSAT} remains constant for a large range of injection current. However through the

long range of injection current the variation of gain is low and offers a small range.

- However for higher gain device, the stable P_{inSAT} is very low (i.e. -12.5dBm) and is available only above 16dB gain values. Medium gain device has better P_{inSAT} (-4dBm) and is available when device is operated at small signal gain above 7dB.
- Low gain devices have high P_{inSAT}.
- P_{inSAT} in low gain devices increase with increasing gain and vice versa, and do not provide a region where the device could be operated at stable P_{inSAT} with varying gain.

From the analysis of the measurements taken on the 4 different SOAs, we realised that any of these commercial SOA can either have high P_{inSAT} or high gain, but not both. For example the SOA offering more than 20 dB gain has -12dBm Input saturation, whereas the device offering high input saturation power like 2 dBm has gain as low 8 dB. The SOA we need for the extended-reach GPONs is required to have high P_{inSAT} and high gain, with P_{inSAT} constant with gain. Unfortunately, all these features cannot be found in any single device so far.

Chapter 5: Bit Error Rate Analysis of System Using SOA

5.1 Introduction

In Chapter 4, we discussed the parametric measurements performed on a number of commercial SOAs using a continuous wave-CW probe. The main objective of measurements performed is a quantitative analysis of amplification response of an SOA towards variety of input optical power values, optical wavelength and amount of bias current. By performing measurements on number of different commercial SOAs, the dependence of device structure on the device behaviour was also analyzed.

The saturation characteristics of SOA at high optical inputs, as discussed in the last chapter, suggest that the device can be used at optical power values less than the saturation power for a linear response. However, in this chapter we will study the effects of very low optical power values as well, on the fidelity of the signal.

This chapter presents the analysis of optical signals' distortion and errors added when amplified by an SOA. For this purpose, instead of CW probe an optical signal containing known information was amplified by the SOA and then compared with a copy of original information so the errors or distortion added by amplification process could be measured. Bit error rate analysis of digital signal is the best way to analyse the performance of the system the signal travels through.

5.1.1 Bit Error Rate – BER

Bit error ratio or Bit error rate - BER, by definition is the ratio of the number of bits or blocks received incorrectly by the receiver in a specific time period, to the total number of bits or blocks of data received.

$$\mathrm{BER} = \frac{\text{Number of erroneous bits received}}{\text{Total number of bits received}} \qquad \text{Eq 5-1}$$

BER is an important parameter with regards to fidelity of information and the performance of a data communication system. In mobile and wireless communication a ceiling BER of 10^{-3} is required, which means that one in a thousand bits could be erroneous. For telephone the BER ceiling is 10^{-6}. Optical communication is safe, fast, and reliable therefore a BER value of 10^{-9} is standard for an optical communication system. This means that only one erroneous bit in a billion bits is acceptable. By erroneous bit we mean receipt of logic one by the receiver whereas logic zero was sent and vice versa. The BER standard for optical communication is strict so that minor abnormalities, if occur could be detected and rectified.

5.1.2 SOA in Future Extended-GPONs

Referring to our discussion in section 2.6.3, that for the purpose of implementation of extended-GPON standard, the number of users directly connecting OLT are to be increased to 128 and the OLT to ONU distance be increased from 20km to 60km without the need of any active components.

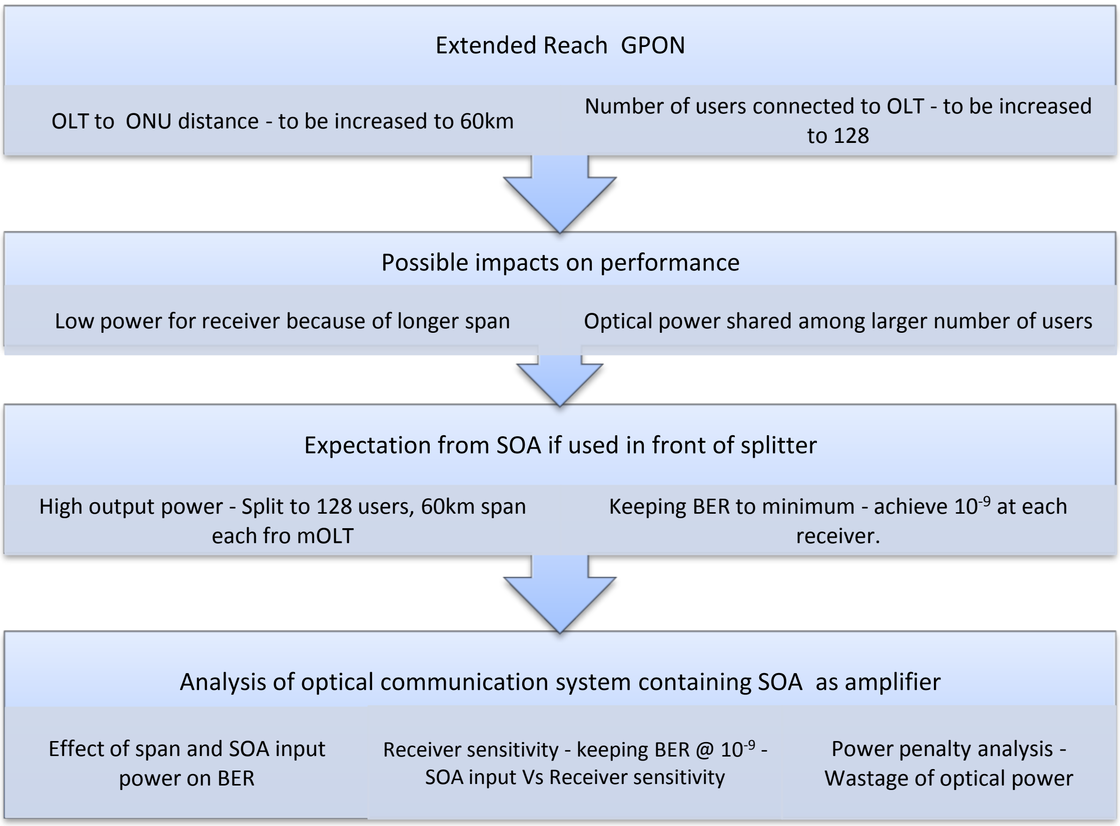


Figure 5-1: Future extended GPON and the SOA – Target and tasks

Figure 5-1 explains the problem and summarizes in the form of a procedural depiction the background for BER analysis of SOA and as to why and how it can be improved in order to serve as amplifier infront of the splitter in the perspective of extended GPONs. As mentioned in the last step of the procedure chart in Figure 5-1, three kinds of analysis will be performed on an SOA in this chapter:

- Effect of receiver sensitivity and SOA input on BER
- Measurement of receiver's sensitivity at BER = 10^{-9}.

5.2 Experimental setup for BER measurements

In order to measure the effect of different conditions on the BER of the optically amplified system, a system of measurements was setup and measurements were taken in a wide variety of operational conditions. In this chapter we will discuss the results of the BER measurements performed on optically amplified system based on SOA and analyse the findings in the perspective of extended GPONs.

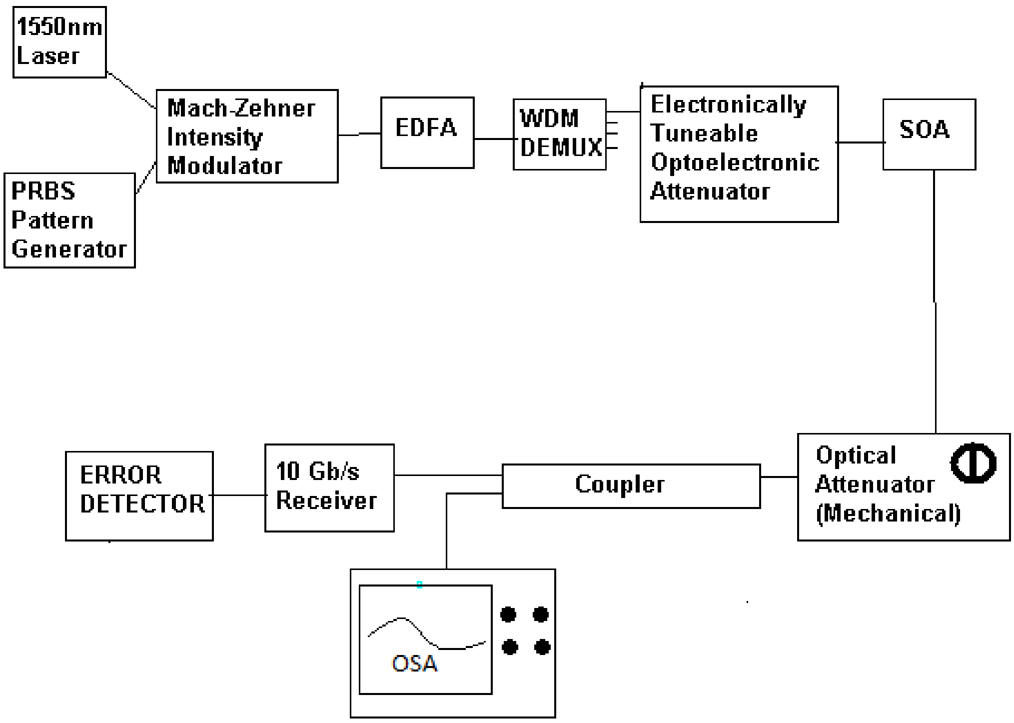


Figure 5-2: Experimental setup for BER measurements (will replace this figure with word art)

The experimental setup for BER measurement is shown in Figure 5-2. The components and their purpose in the experimental setup are described below:

- *PRBS Generator:* In order to simulate a real signal we used a pseudo random bit sequence or PRBS as main data signal. As PRBS is a chain of 1s and 0s, in an order which is *pseudo* random (i.e. not fully random) and is known bit sequence. Therefore it is possible to expect whether there should be a logic zero or one at any specific time at the receiver's end.
- *Laser:* 1550nm coherent laser source was used as optical carrier.
- *Mach-Zehnder Modulator:* The PRBS data was modulated on to the carrier (i.e. laser) using Mach-Zehnder Modulator. This provided us with an optical data signal.
- *EDFA:* It was observed that Mach-Zehnder modulator attenuates the signal by at least 5dB. If the signal power is not strong enough, a booster is used to bring the signal power to required level. We used an EDFA for one of the SOAs with higher P_{inSAT}. The EDFA was also used to supply the SOA with a variable input power in addition to the variable attenuator.
- *WDM- Demux:* It was observed that the EDFA had an undesirable noise peak at about *1520nm*, which was not desirable. Therefore a WDM demux is introduced after the EDFA in order to allow only 1550nm signal into the SOA.
- *Mechanical Attenuator:* A mechanical attenuator is used to emulate the attenuation suffered by signal on its way to the receiver.

- *Coupler:* A coupler placed in front of receiver divides the signal in to two equal parts. Half of the signal is converted into electrical signal by the receiver for error analysis and other half for the optical probe input of the oscilloscope. The coupler was used for two reasons: firstly because of mechanical attenuator it was difficult to find the exact optical power that was going into the receiver. Secondly because we wanted to look at the eye diagram of the signal in the optical domain. Splitting the output of the SOA into two equal parts enabled to simultaneously perform error analysis and the optical waveform viewing.
- *10 GHz Lightwave receiver:* One output of the coupler was received by a 10Gb/s optical receiver, which converted the signal to electrical for further analysis in the electrical domain.
- *Error Detector:* An error detector is electronic equipment which compares two signals and counts the number of mismatched bits in a specific period of time. The electrical output of the receiver is given into the error detector for BER measurements.
- *Pulse generator:* A single 10Gb/s pulse generator was used to provide simultaneous clock to PRBS generator, error detector and the optical receiver for the purpose of synchronization. All the measurements discussed in this chapter have been done using 10 Gb/s PRBS data.
- *Oscilloscope:* A 10GHz oscilloscope with both electrical and optical input probes was used. The oscilloscope allowed us to view and analyse the eye diagram and the pattern of the optically amplified signal.
- *Optical Spectrum Analyzer- OSA:* An OSA was used to measure the power as well noise in the optical signal. It is pertinent to mention here that one of the outputs of couple was permanently given to receiver for error rate measurement. Therefore, the other output was occasionally viewed either on oscilloscope or OSA. The OSA was operated with a resolution bandwidth – RBW of 0.2 nm.

5.3 BER Profile of the Signal Amplified by SOA at Receiver end

5.3.1 Introduction

The SOA amplifies the signal but it also adds few undesirable features to the signal, increasing the minimum signal power required by the receiver to read the signal correctly. For instance, consider a receiver that is able to read the signal carried by 5dBm optical signal directly coming from emitter. But if the same 5dBm signal is coming from an SOA, the receiver may not be able to read the message because of the erroneous features added by SOA and would probably require higher signal power.

The main idea behind these measurements is that the optical signal may go through attenuation or other losses after being amplified by the SOA on its way to the receiver, thus affecting the BER. In addition to other factors, the BER in SOA amplified systems might be affected by two very important parameters:

i. SOA input signal power
ii. The strength of amplified optical signal that reached the Receiver

Study of SOA input power is important as it defines the mode of operation of the SOA. For a low input power there may be dominant noise effects whereas larger optical power may drive the SOA into saturation. In the next sections, we will study the role of these parameters in error rate of signal.

We already discussed in the previous sections that perspective extended-GPONs is expected to have extended span between OLT and user. As the attenuation effects are directly proportional to length of fiber, the optical power that reaches the user will decrease in case of extension of span. BER of the signal received at receiver's end describes the effects of both variation in SOA input power and the loss of signal strength due to both splitting and long span.

As discussed, two variable attenuators are used in the measurement setup – signal power loss is emulated by a variable attenuator used in front of the receiver and the other one is placed in front of the SOA to vary the input SOA power.

5.3.1.1 Results - BER Response to Receiver Power

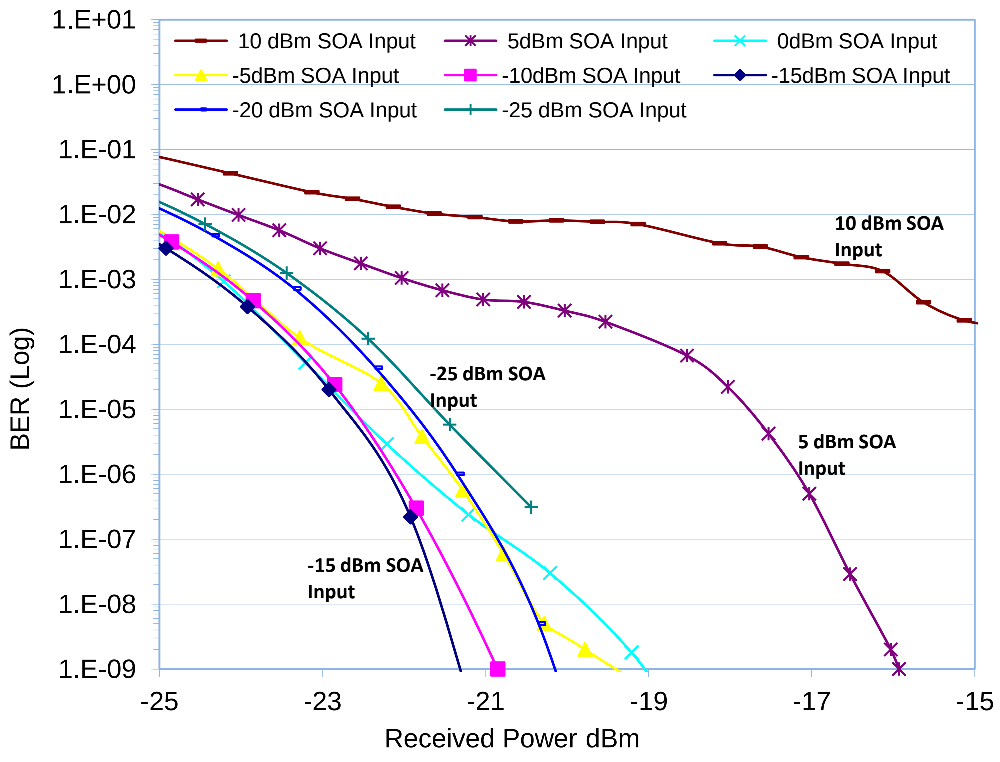


Figure 5-3: Receiver input power Vs. BER for different SOA input powers –Device 21909

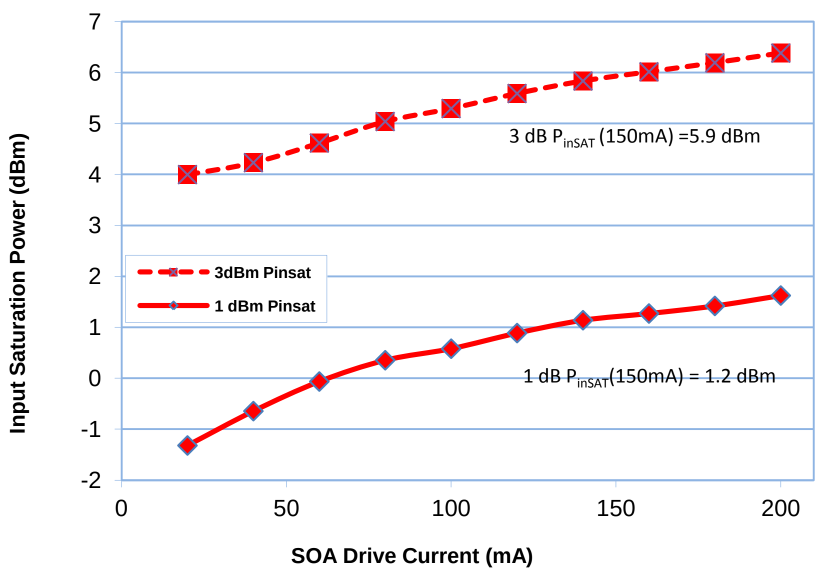


Figure 5-4: 1dB and 3dB P_{inSAT} for device 21909

The plots for SOA inputs of -25, -20, -15, -10, -5, 0, 5, and 10dBm are shown in Figure 5-3. The device 21909 has been used for these measurements. Parametric measurements on the device were analyzed in Chapter 4. Figure 5-4 is a trace of P_{inSAT} vs drive current from Chapter 4 for the purpose of reference to the saturation points at 150mA. Both 3dB and 1dB P_{inSAT} curves are shown for comparison. For BER measurements the device was driven at 150mA at which 1dB P_{inSAT} is approximately 1.2 dBm.

We can see from the BER curves shown in Figure 5-3, that irrespective of the SOA input power, there is a general trend of very high BER (approx 10^{-1}) at low receiver powers (LHS of the Figure 5-3). In general, low received power can refer to:

- Either a very long span or other source of attenuation added to the signal before it was received or
- Low output power of the SOA

In the experimental setup we have used an attenuator after SOA which decreases the signal strength before it is received by the receiver.

A serial digital optical signal is a series of optical pulses, with logic zero as zero power (ideally) and logic 1 as some finite optical power. When the received power is low, the logic zero and logic 1 level come very close resulting in decrease of extinction ratio. Even a minor fluctuation in this situation can result in logic 1 be received as logic 0 and vice versa. That is why there is generally a high BER at low received power values. This phenomenon is general and should hold for both amplified and non-amplified signal. The BER will remain high no matter the SOA input was high or low, if the optical power that finally arrived at receiver is low.

However when the signal power received is increased, the BER decreases significantly. The behaviour can be observed from the right hand side of the plots for SOA inputs of -25 through 0dBm. The error floor seems to be significantly low for these curves.(error floor not shown in plot)

When the received power is reasonably high, the extinction ratio is high and the receiver is able to adjust its threshold to an adequate level and therefore the probability of erroneous bits received becomes low as compared to low received power. In general, by increasing the received power the BER decreases. This conclusion remains true apart from the situation when the SOA is operated in saturation region.

The saturated output of SOA if carries a signal to the receiver such that received power is reasonably high, there might still be high error rate. For 5dBm SOA input, though the error floor seems to be well below 10^{-10} the behaviour is different. This suggests that increasing the SOA input might increase the BER. This is further confirmed by the plot for 10dBm SOA input, which ceases to go below an error floor of 10^{-5}. The observation suggests that operating the SOA in saturation region might increase the error rate of the signal and this error cannot be removed by increasing the received power.

From Figure 5-3, we can observe that for very high SOA input power, like 10dBm the BER does not improve beyond a certain value even if the received power is high. Referring to our analysis in last chapter and the Figure 5-4, the plot 5dBm and 10dBm lie in the saturation region of the device. This means that the signal received by the receiver is a saturated output of the SOA. The effect of gain saturation of SOA will be discussed in detail in later sections.

It is interesting here to note that in parametric analysis of SOA in Chapter 4, we could not find any problem with saturation apart from the decrease of gain, and the SOA could still be used. However from BER analysis we have observed that saturation of gain is not the only problem in saturation region operation; increased BER due to saturation may also result in loss of information.

5.4 Receiver's Sensitivity Measurements

5.4.1 The Receivers Sensitivity-R_x

From previous section, we conclude that higher SOA input signal power, the BER is greater. In order to get a clear picture and to find the limits imposed on the output of SOA. Further experiments and measurement were taken in terms of maximum tolerable BER. As discussed in the Section 5.1.1, the maximum tolerable BER is normally taken as 10^{-9}. The light wave receiver requires that the optical signal should be strong enough to be received without errors or to keep BER to the minimum. There is a minimum level of optical power, which the optical signal must have in order to be received by the receiver with BER equal to or less than 10^{-9}. This minimum acceptance level of received power refers to receiver sensitivity – R_x.

It is important to mention here that for a situation where high receivable power is required by the receiver, conventionally the sensitivity is said to be '*Low*'; and similarly if a low optical power can keep the minimum BER, the receiver sensitivity is said to be '*High'.* In other words, the receiver sensitivity R_x is a receiver's response-parameter to the incoming signal. A high sensitivity would mean a good response and receiver's good ability to receive error free (or minimum BER) data carried by even a low optical power signal, and vice versa.

Receiver sensitivity is important as it defines the span the signal can travel in the fiber before being received. High sensitivity *(i.e. low power required)* would facilitate longer spans and accommodate channel. The optical signal amplified by SOA is expected to effected by two major factors

1. Saturation
2. Signal Noise

As discussed in previous chapters, the saturation of SOA occurs when the signal power exceeds a certain level. Hence the saturation affects the signal's BER at high SOA input power results in higher receiver power requirement.

Optical signal to noise ratio – OSNR is another important parameter which plays an important role in the estimations of errors and sources of errors in the optical transmission system. Noise normally influences at low power where OSNR is very low.

We took optical power measurements from OSA in decibel scale. The signal power and noise can both be visually measured in decibels. However noise adjustment and estimation of OSNR cannot be done directly from the decibel measurements, since subtraction and addition in decibel refers to division and multiplication in linear scale. Because noise is added to the signal, we need to convert the observed siglnal power and the noise measurement into linear scale, subtract the noise from the observed signal power and then convert it back to decibels. This way we will get the noise adjusted power. Mathematically

$$OSNR_{Linear} = \frac{Signal's\ Optical\ Power_{Linear\ Units}}{Noise\ Optical\ Power_{Linear\ Unit}}$$

Equation 5.1

$$OSNR_{dB} = Signal's\ Optical\ Power_{(dB)} - Noise\ Optical\ Power_{dB}$$

Equation 5.2

The same setup as discussed Section 5.2 and shown in Figure 5-2 was used to perform the receiver sensitivity measurements. At any specific drive current, the input to the SOA was varied using an EDFA. The variable attenuator between the receiver and the SOA was used to adjust the optical power to a level that offer a BER value of 10^{-9}. This procedure was repeated for several drive currents.

5.4.2 Sensitivity Measurements: Results and Discussion

Figure 5-5 shows the results for selected currents. We can clearly see a parabolic profile of the graphs, which is consistent with our discussion in Section 5.4.1 . In general all the graphs show a specific trend, i.e.:

- At low SOA input power, higher receiver power is required to keep BER to a minimum.
- In the middle portion, the required receiver power is lowest. This is the desired behaviour where the required BER level can be achieved with minimum receiver power or *highest* sensitivity.
- At high SOA input powers, the high receiver power is required to achieve the required BER of 10^{-9}. This means receiver sensitivity is *low* if the SOA input is increased. The effects of not decreasing the sensitivity of the receiver will be high BER.

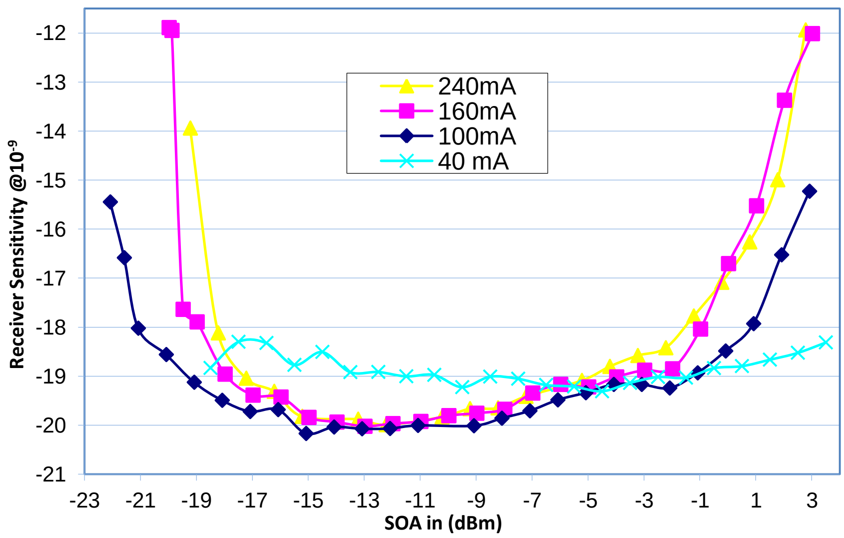


Figure 5-5: SOA Input Power Vs Receiver sensitivity device 21909

There trend can be observed when we compare the curves for different currents. Following observations can be made from the plot:

- *Effect of current at low SOA input power value:* From LHS of figure we can observe that at low input power where receiver sensitivity is generally low, the sensitivity for high current is even lower than the small current value. This is because of higher charge carrier density and lower amount of stimulated emissions as the input power is low, and as a consequence the ASE becomes dominant. That is the reason that a lower current results in comparatively better sensitivity at low input power as the superfluous carriers are lesser in number.

- *Effect of current at medium input power where sensitivity is generally higher:* Middle part of sensitivity curve is where SOA input is neither very low nor saturated. The sensitivity in this part is generally higher for all currents.

However for higher current values the sensitivity is better than the lower current. This is because higher input power with higher carrier density results in higher amount of stimulated emissions, (provided the device is not saturated) and the signal is less affected by high current noise as OSNR becomes higher.

- *Effect of current at high input power where sensitivity is generally decreased:* At high input signal power the SOA is normally saturated.
- *Effect of current in general on the sensitivity:* In general, the receivers sensitivity bowl become narrower for high current i.e. the region of operation or high sensitivity get narrower with increase in drive current. However the level of highest sensitivity in the middle also improves with increase in current. So it is a trade off between increasing the best sensitivity and widening the region of operation.

For a better and clearer picture, 100mA curve from Figure 5-5 is redrawn in Figure 5-6. Gain and OSNR are also plotted with respect to input current in same graph. The purpose of adding gain and OSNR traces to the plot is to analyse their effects on the receiver sensitivity. The effect of OSNR in small SOA input power values and the saturation effects on high SOA input values have already been discussed a number a time in this chapter. Therefore, very briefly we discuss the picture the plots present when combined.

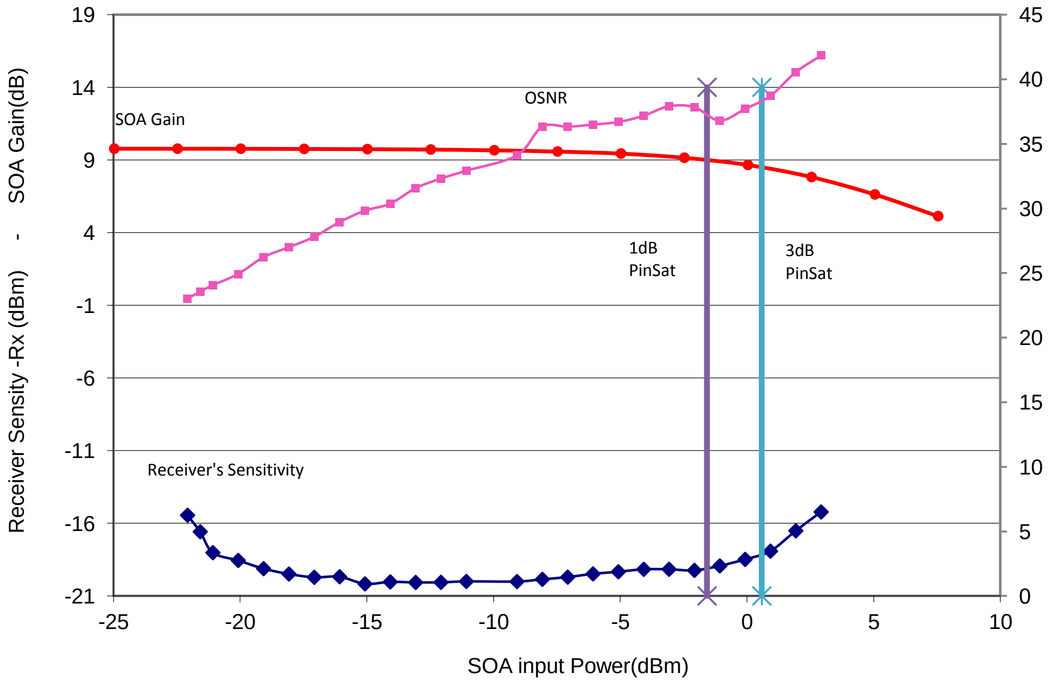


Figure 5-6: Receiver Sensitivity, Gain and OSNR - all as function of SOA input power for device 21909

As we can see in the Figure 5-6 that the OSNR is increasing with the increasing signal power. Therefore the system noise has comparatively minor impact on the receiver's sensitivity at high SOA input power values. In fact, the OSNR gets even higher when the sensitivity starts decreasing again; hence there is no or little evidence of involvement of noise on the fall of receiver sensitivity on right hand side of curve or at higher SOA input power.

However, in the same figure we can see that it is the saturation region of the SOA where the sensitivity of receiver rises again after touching the minima. Therefore there is more probability that SOA gain saturation is the main factor causing BER to increase thus imposing higher optical power requirement for at receiver's end.

5.4.2.1 1dB saturation

From Figure 5-4 we can see that 1dB P_{inSAT} for the device 21909 is between -1.5 and 2dBm, whereas 3dB P_{inSAT} is between 4 and 6.5 dBm for this device. It may be interesting to note from Figure 5-5 and Figure 5-6 that the fall in sensitivity is approximately in the 1dB P_{inSAT} range, and when the SOA input power is increased to 3dB P_{inSAT} level, the sensitivity drops considerably. Hence 1dB P_{inSAT} seems to appear as a potential candidate to replace 3dB saturation threshold in the analysis of SOA in optical communications system from the perspective of error analysis. In addition the results justify our choice of 1dB saturation point for parametric analysis in Chapter 4.

5.5 Power Penalty in system using SOA

Power penalty refers to additional power required by a receiver to keep BER value at certain required value in a changed scenario. Mathematically power penalty is a ratio and has no linear units if the power is assessed in linear units and dB if power units are decibel.

For linear units

$$Power\ Penalty = \frac{P_2}{P_1} = \frac{P_1 + \Delta P}{P_1}$$

Equation 5.3

And in dB

$$Power\ Penalty(dB) = P_2(dB) - P_1(dB)$$

Equation 5.4

Here P_1 is power required in good conditions when the receiver sensitivity is high and less power is required. P2 is the power required in changed scenario. ΔP is the additional power imposed by changes in the system or environment.

For instance, a receiver requires the signal power to be 0.5mW in order to be received with a BER of 10^{-9}. Suppose there are changes in the system that adds noise or other effects e.g. SOA saturation etc. Under these conditions, the BER increases and in order to keep BER low, the signal power has to be increased to 0.75mW. The ratio by which the power has to be increased is the power penalty imposed by the new condition and is equal to (0.75mW)/(0.5mW) = 1.5, i.e. a 50% increase in signal power required to keep BER low.

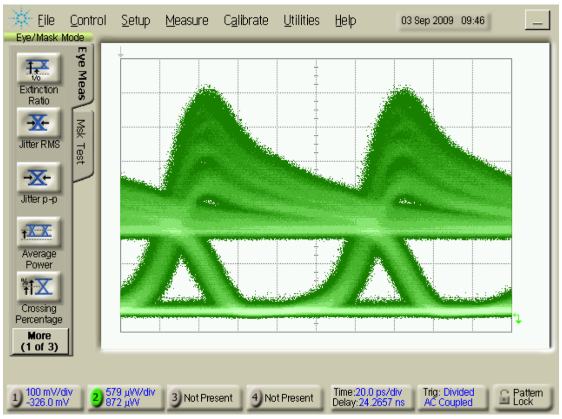
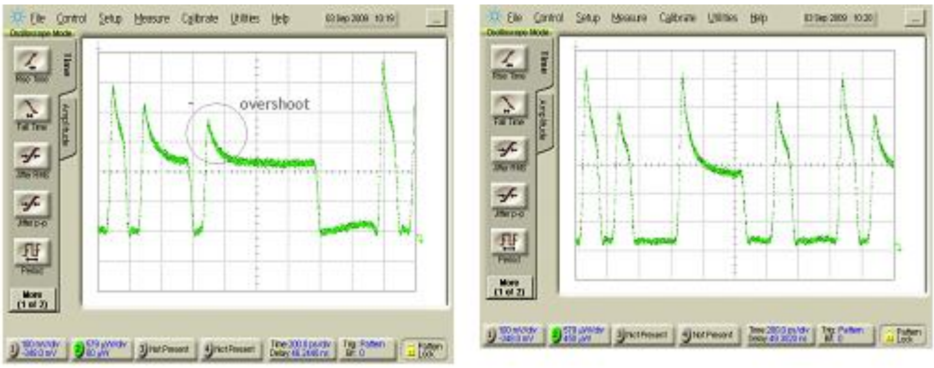


Figure 5-7: Mask mode view of the eye diagram of the optical signal with overshoots



(a)

(b)

Figure 5-8: Signal Overshoot captured on Oscilloscope. Scale x-axis: one division =20ps, y-axis: 1 div=579µw

In SOA amplified transmission gain saturation imposes a power penalty due to optical power wasted in signal overshoots. In digital transmission for logic zero level there is ideally zero power, and practically very little optical power carried by the signal. Thus even if the device is in saturation, the zero segment of the wave will be in small signal region. So zero level will not be affected by the saturation. However when the signal changes from zero to one, the device again goes into saturation and the gain has to go down. But the device is not able to switch the gain very quickly, so the signal power rises first as if it has the same small signal gain, but then quickly comes down to the saturation regions gain. This going up and down is called overshoot. Figure 5-7 shows a mask mode view of the signal in saturation where Figure 5-8 is the pattern locked snap of the same signal captured from oscilloscope. The overshoots are clearly visible in both pictures. As the SOA will not be operating in the upper gain regions anyway, the power consumed in going up and down is a waste of power, and same amount of additional power will be required to accommodate this loss.

There are also visible minor undershoots, when the signal changes from 1 to 0. This has the same explanation as for the overshoot. The system while in logic 1 state or high incident population state is adjusted to decreased emission amplitude in order to keep the equilibrium. When the level of signal changes to low power level, the system treats the signal with the same response as it was treating the high power, thus there is low power output initially. However later on, low power resulting in lesser stimulated emissions, initially gives way to increased availability of carriers, and adjust accordingly toward the equilibrium at some level a bit higher than the undershoot.

Undershoots are very small as compared to overshoots. There are a number of reasons that can explain this difference; one reason for this behaviour is that the system is in saturation region, and decrease in power means a decrease in saturation level, and thus the system will be able to adjust easier than the overshoot. Another reason is presence of spontaneous emissions which does not let the output go down.

After explaining the causes of overshoots, let us consider the different overshoots shown in Figure 5-8 (a, b). We can see that the size of overshoot is not the same for all transitions. The overshoot for a transition from 'zero' to 'one' level after multiple continuous *'zeroes'* is bigger than the one that comes after single or less number of zeros. That means if signal level is low for longer time and then transits to higher level there will be bigger overshoot, and if it remains low for smaller time, the overshoot is smaller.

For high power, (logic 1), in saturation region, the SOA is adjusted in a state of equilibrium which is suited for very high number of photons. When the signal changes to lower level (logic zero) the new state has to be developed in order to entertain the less number of photons. The system keeps adjusting itself toward to the best possible equilibrium state for the current low power. Therefore, the situation of remaining low for a single logic zero is different from remaining low for more continuous zeros.

This is the reason that when there is logic one after small number of zeros, the overshoot is smaller, and when it comes after large number of zeros, the overshoot is bigger. Now the effect of remaining at logic zero is not seen on the graph. This is probably because of the spontaneous emission which hides the effects and adds power to low level.

The vertical widening of power level for logic '1', affects the eye opening and the decision level. This imposes severe restrictions on the signal power resulting in extra power needed, which is understood as power penalty due to loss of extinction ratio. Loss of extinction ratio can occur due to noise as well as gain saturation.

5.6 BER analysis conclusion

BER analysis of SOA-amplified signal suggests that contrary to the linear regime findings in parametric analysis, operating the SOA at very low signal power values is also not suitable because of high BER caused by noise. In saturation region the error analysis appears to be in-line with the findings of parametric analysis of SOA amplified system. The BER of the system increases as SOA enters the saturation region. As a result the sensitivity of the receiver drops. However, the drop in receiver's sensitivity can be accommodated by increasing the receiver's power as long as the error floor is below 10^{-9}. Referring to our discussion in Section 5.3 and Figure 5-3 very high signal power might result in complete sensitivity loss as the error floor goes rises significantly close to 10^{-9}. Therefore the region of operation is a medium range of signal power values that lies between noise affected low values and saturation affected high values.

The error rate measurements presented in this chapter are for a low gain device which has a higher P_{inSAT}. The input dynamic range appears to be between -20 and -0dBm (including the region where there is minor loss of sensitivity). Receiver's best sensitivity is around -20dBm available between -15 and -1dBm SOA input signal power. This range is available for 9dB SOA gain as this SOA has low gain. The behaviour for a high gain SOA can be perceived from these results. The high gain SOA e.g. 21923 can offer around 23dB gain as discussed in parametric measurements in Chapter 4. High gain can help reaching users further apart from the SOA. However, with high optical, the same device has P_{inSAT} of about -12dBm, which is very low. As the sensitivity starts dropping at 1dB P_{inSAT}, we can expect that the higher edge of high sensitivity input range for this high gain device might be 10dB lower than the low gain device discussed in this chapter (i.e. 21909), which might narrow the dynamic input range of the device.

Chapter 6: Conclusions and future work

6.1 Summary & conclusions

The discussion presented in this thesis is based on the measurements and analysis of SOA for its suitability as in-line amplifier in future extended-GPONs. In order to extend the reach and number of users of current GPON structure, an optical amplifier is required to be installed in front of burst mode receiver, that can not only provide a high gain but should also be able to switch the gain level according to the size of incoming data burst so that all the busts can be amplified to similar size as per requirement of the burst mode receiver. An SOA with a very high recovery speed makes a potential candidate for this application. However the SOA has its own limitations. Strong signals that need very little gain, cannot be amplified with SOA as the SOA when operated at low gain regime, suffers a low saturation power, and the signal power might be greater than the saturation power. From this perspective, parametric and error rate measurements were performed and discussed in this thesis in order to make a basis for the further investigations on prospects of future employment of SOA in extended GPONs.

The first set of experiments on system using SOA was parametric measurements using a CW laser on a number of high and low gain commercials SOAs. The high gain devices (i.e. approx 25dB) appeared to have a comparatively low P_{inSAT} (approx -12dB) thus limiting the ceiling for SOA input. In addition the high gain devices have small range in which the gain could be varied using drive current. On the other hand, the low gain devices (i.e. 9dB approx) have higher P_{inSAT} (-1 to 0dBm) allowing the input range to be greater. However the low gain remains a barrier.

The second set of experiments is concerned with the bit error rate analysis of the optically amplified system using SOA. In these experiments a 10 GHz PRBS signal is amplified using SOA and compared with original signal in order to find the rate of bit errors added by system amplified by SOA. The initials measurements on different SOA input power values showed that for high input power values (e.g. 5 or 10dBm) the error floor remains very high thus suggesting that SOA should not be operated at very high signal power, as the error rate cannot be decreased by increasing received power. Low signal powers like 1dB and below seemed to be suitable as the error floor seemed to be well below 10^{-9} for these inputs.

The parametric measurements in Chapter 4 suggest linear operation at low SOA input power values. However the error analysis shows at very low signal power values the noise dominates and results in high BER.

Therefore at very low and very high signal power values the SOA amplified system has very low sensitivity. Hence the best range of operation for SOA input is medium range where the SOA suffers neither a low OSNR nor saturation. The width of SOA input range of operation for a low gain (i.e. 9dB) SOA is about 20 dB (i.e. -20 to 0dBm). The ceiling of this range is defined by the P_{inSAT}. The P_{inSAT} for high gain device (i.e. 21923) is -12dBm which very low, and hence upper limit of SOA input might be lower than the low gain device. Therefore a trade off is expected between input dynamic range and high gain while switching between high and low gain SOAs.

6.2 Possible solutions

From the analysis in this thesis it seems that the SOA has the capacity to fulfil the requirements as an amplifier for extended GPONs. However the limitations imposed by the SOA's natural response need to addressed and eradicated. Saturation at high power is a characteristic of SOA that cannot be removed. In normal operation a higher saturation power can be acquired but is only available to high gain, whereas low gain is possible only with low saturation power. Experiments were performed on different devices, and the results concluded that the required characteristics like high and stable saturation power, wider control over gain and higher dynamic range etc can be easily found in these devices. However all of these characteristics cannot be found in a single device and a trade off is always required.

Adjustable gain clamped SOA – AGCSOA: Low Gain with high saturation power can be achieved by gain clamping. In gain clamping the SOA is kept at high current so that the saturation power is high providing large signal dynamic range. Instead of drive current the gain is decreased or clamped to a lower level through some lasing technique. Thus through gain clamping a low gain level can be achieved without compromising over the high saturation power.

The GCSOA still lacks the ability to adjust the gain. Most of the GCSOA techniques were based on either fixed structure (monolithic fabrications e.g. [129]) or in some cases physically quantized adjustable clamping level control parameters (e.g. reliance on fiber grating etc)., and thus limiting the speed with which the gain can be adjusted.

The handicap can be addressed through the dynamic adjustments of the clamping level of GCSOA. The idea is known as Adjustable GCSOA or AGCSOA [114]. In AGCSOA, the SOA is driven at fixed current, and the gain is clamped through the lasing mode resonating in the opposite direction. This lasing mode is provided by another SOA, with adjustable drive current. So in short, in AGCSOA, the gain of an SOA is controlled through the drive current of another SOA, which is connected to the main SOA in a ring cavity. AGCSOA has proved to provide a wide input dynamic range for a wide gain dynamic range at the same time.

However the AGCSOA still has to refine as it lacks the ability to integrate. The AGCSOA uses isolators to avoid back reflections. These isolators are optical components that are difficult to integrate.

Multi-section SOA is designed that deal with gain and P_{inSAT} separately.

Multiple SOAs: High gain and high P_{inSAT} SOAs used in parallel and the incoming signal is passively let go by low gain device and be amplified by high gain device. A coupler can be used to divide the SOA input into e.g. 1:7 or similar ratio, with smaller portion amplified by high gain SOA and bigger portion by the high P_{inSAT} device.

6.3 Suggestion for future research projects

- Power penalty measurements based on methodology presented in this thesis can be done to find the exact losses due noise and saturation by measuring the amount of overshoots and power loss in extinction ratio.
- Follow up of the BER, sensitivity and power penalty analysis to be performed on AGCSOA.
- RLC circuit modelling of SOAs: The overshoots and recovering to equilibrium level is similar to over damped or critically damped RLC circuit response. Discrete electronics components are easy to manage and are inexpensive.
- Parametric and BER measurements on a compound amplifier i.e. multi-section or AGCSOA [71, 114].
- The amount of attenuation and other effect can be simulated for exactly 60km fibers by modifying parameters for required solution.

References

1. Gagliano, M., *Green symphonies: a call for studies on acoustic communication in plants.* Behavioral Ecology, 2013. **24**(4): p. 789-796.
2. Frisch, K.V., *All Lives ... All Dances ... All Is Loud + Dancing Bees.* Parabola-Myth Tradition and the Search for Meaning, 1979. **4**(2): p. 81-82.
3. Liffen, J., *Telegraphy and Telephones.* Industrial Archaeology Review, 2013. **35**(1): p. 22-39.
4. *Morse code is dead. Long live morse code.* Ieee Spectrum, 2007. **44**(2): p. 8-8.
5. Dufresne, C., *From Bell's first telephone to the cell phone (A history of communication).* Historia, 1999(627): p. 68-+.
6. Tejkal, V., et al., *The impact of modulation formats used in passive optical network.* Tsp 2010: 33rd International Conference on Telecommunications and Signal Processing, 2010: p. 421-425.
7. Cheung, W.M., M.K. Chang, and V.S. Lai, *Prediction of Internet and World Wide Web usage at work: a test of an extended Triandis model.* Decision Support Systems, 2000. **30**(1): p. 83-100.
8. Gibbens, R., R. Mason, and R. Steinberg, *Internet service classes under competition.* Ieee Journal on Selected Areas in Communications, 2000. **18**(12): p. 2490-2498.
9. Burstyn, H.P., *Electronic Mail Services.* Datamation, 1985. **31**(22): p. 133-&.
10. Ferskoweiss, H., *Electronic Mail - the Emerging Connection.* Personal Computing, 1985. **9**(1): p. 71-&.
11. Ferskoweiss, H., *The Side-Effects of Electronic Mail.* Personal Computing, 1985. **9**(1): p. 72-72.
12. *Electronic Mail Brings Back the Telegram.* New Scientist, 1985. **107**(1474): p. 28-28.
13. Gore, D. and M. Lee, *VoIP: Teaching new technology for a converging industry.* Imsci '07: International Multi-Conference on Society, Cybernetics and Informatics, Vol 2, Proceedings, 2007: p. 233-238.

14. Chen, C.N., et al., *Measuring the Perceptual Quality of Skype Sources.* Computer Communication Review, 2012. **42**(4): p. 521-526.
15. Kumar, V.B. and D. Subramanian, *"NetPhone"-Reintegrating the net phone.* 2007 International Symposium on Integrated Circuits, Vols 1 and 2, 2007: p. 164-167.
16. Saif, U., et al., *Poor man's broadband: Peer-to-peer dialup networking.* Computer Communication Review, 2007. **37**(5): p. 7-16.
17. Saif, U., et al., *Internet for the Developing World: Offline Internet Access at Modem-speed Dialup Connections.* 2007 International Conference on Information and Communication Technologies and Development (Ictd), 2007: p. 75-87.
18. Granville, F., *Broadband system speeds Internet access.* Edn, 1996. **41**(13): p. 32-32.
19. Laubach, M., *To foster residential area broadband internet technology: IP datagrams keep going, and going, and going (Reprinted from ConneXions, vol 10, 1996).* Computer Communications, 1996. **19**(11): p. 867-875.
20. Grace, A., et al., *Intranet-TV - Video streaming for the World Wide Web.* British Telecommunications Engineering, 1998. **17**: p. 49-55.
21. Manhart, S. and A. Kampa, *A generic architecture for live video transmission.* Broadband European Networks and Multimedia Services, 1998. **3408**: p. 603-610.
22. Banker, R.D., et al., *Technological progress and productivity growth in the US mobile telecommunications industry.* Annals of Operations Research, 2010. **173**(1): p. 77-87.
23. ; Available from: www.three.co.uk.
24. GSMA. *GSMA Announces New Global Research that Highlights Significant Growth Opportunity for the Mobile Industry*. 2012; Available from: http://www.gsma.com/newsroom/gsma-announces-new-global-research-that-highlights-significant-growth-opportunity-for-the-mobile-industry.
25. Arumugam, M., *Optical fiber communication - An overview.* Pramana-Journal of Physics, 2001. **57**(5-6): p. 849-869.

26. Agarwal, G., *Fiber-optic Communication Systems*. 2002, New York: John Wiley & Sons.
27. Hecht, J., *City of Light: The Story of Fiber Optics*. The Sloan Technology Series, ed. A.P.S. Foundation. 1999, New York, New York 10016: Oxford University Press, Inc.
28. Snyder, A.W., *Radiation Losses Due to Variations of Radius on Dielectric or Optical Fibers.* Ieee Transactions on Microwave Theory and Techniques, 1970. **Mt18**(9): p. 608-&.
29. Snyder, A.W. and D.J. Mitchell, *Bending Losses of Multimode Optical Fibers.* Electronics Letters, 1974. **10**(1): p. 11-12.
30. Kaiser, P. and H.W. Astle, *Measurement of Spectral Total and Scattering Losses in Unclad Optical Fibers.* Journal of the Optical Society of America, 1974. **64**(4): p. 469-474.
31. Hayes, J., et al., *Fiber optics.* Connector Specifier, 1997. **13**(4): p. 18-22.
32. Hayes, J., *Fiber Optics Technician's Handbook*. Albany, New York: Delmar Publishers.
33. Gloge, D.C., et al., *Fiber Optic Systems for Terrestrial Applications.* Ieee Journal on Selected Areas in Communications, 1986. **4**(9): p. 1386-1388.
34. Miyamoto, Y., et al., *40-Gbit/s ETDM channel technologies for optical transport network.* Optical Fiber Technology, 2001. **7**(4): p. 289-311.
35. Huang, Y.K., et al., *High-Capacity Fiber Field Trial Using Terabit/s All-Optical OFDM Superchannels With DP-QPSK and DP-8QAM/DP-QPSK Modulation.* Journal of Lightwave Technology, 2013. **31**(4): p. 546-553.
36. Wada, N., et al., *Photonic Technologies for New Generation Network.* 2011 13th International Conference on Transparent Optical Networks (Icton), 2011.
37. Gambling, W.A., *The rise and rise of optical fibers.* Ieee Journal of Selected Topics in Quantum Electronics, 2000. **6**(6): p. 1084-1093.
38. Raghavan, T.S., V.L. Babu, and S. Suresh, *Access networks evolution & revolution.* 2005 Ieee International Conference on Personal Wireless Communications, 2005: p. 207-211.
39. Korcek, D. and J. Mullerova, *Steep optical filtering for next generation optical access networks.* 18th Czech-Polish-Slovak Optical Conference on Wave and Quantum Aspects of Contemporary Optics, 2012. **8697**.

40. Elbers, J.P., et al., *High-capacity WDM/ETDM transmission at 40 Gbit/s line rate.* Optical Amplifiers and Their Applications, Proceedings, 2001. **44**: p. 193-195.

41. Oxenlowe, L.K., *Tutorial: Terabit/second OTDM Systems.* 2011 Ieee Photonics Conference (Pho), 2011: p. 650-651.

42. Kelly, A.E., *Optimization of Semiconductor Optical Amplifier for optical networks*, in *Electronic Engineering*. 1999, University of Strathclyde: Glasgow. p. 188.

43. Brackett, C.A., *Dense Wavelength Division Multiplexing Networks - Principles and Applications.* Ieee Journal on Selected Areas in Communications, 1990. **8**(6): p. 948-964.

44. Prucnal, P.R. and M.A. Santoro, *Spread Spectrum Fiberoptic Local Area Network Using Optical-Processing.* Journal of Lightwave Technology, 1986. **4**(5): p. 547-554.

45. Kwong, W.C., P.A. Perrier, and P.R. Prucnal, *Performance Comparison of Asynchronous and Synchronous Code-Division Multiple-Access Techniques for Fiberoptic Local Area Networks.* Ieee Transactions on Communications, 1991. **39**(11): p. 1625-1634.

46. Haji, M., *Optical code division multiple access systems in AlGaInAs/InP* in *School of Engineering*. 2012, University of Glasgow: Glasgow. p. 159.

47. Faulkner, D.W. and D.I. Fordham, *Broad-Band Systems on Passive Optical Networks.* British Telecom Technology Journal, 1989. **7**(2): p. 115-122.

48. Scholl, F.W. and M.H. Coden, *Passive Optical Star Systems for Fiber Optic Local Area Networks.* Ieee Journal on Selected Areas in Communications, 1988. **6**(6): p. 913-923.

49. Atterbury, B. and M. Kelsey, *Gigabit Ethernet passive optical networks.* Long-Haul and Access Networks, Optical Metro and Wdm, 2001: p. 345-354.

50. *Repeater Electrically Boosts Light Signals for Optical-Fiber Communications.* Bell Laboratories Record, 1973. **51**(7): p. 222-222.

51. Ueno, Y. and Y. Ohgushi, *40 Mb-S and a 400 Mb-S Repeater for Fiber Optic Communications.* Ieee Journal of Quantum Electronics, 1975. **11**(9): p. D78-D79.

52. Desurvire, E., J.R. Simpson, and P.C. Becker, *High-Gain Erbium-Doped Traveling-Wave Fiber Amplifier.* Optics Letters, 1987. **12**(11): p. 888-890.
53. Mears, R.J., et al., *Low-Noise Erbium-Doped Fiber Amplifier Operating at 1.54-Mu-M.* Electronics Letters, 1987. **23**(19): p. 1026-1028.
54. Alwayn, V., *Optical Network Design and Implementation*. Networking Technology series. 2004: Cisco Press.
55. Kaiser, P., *Impurity Content and Spectral Losses of Low-Loss Bulk Glasses for Optical Fibers.* American Ceramic Society Bulletin, 1973. **52**(4): p. 385-385.
56. Gisin, N., *Statistics of Polarization-Dependent Losses.* Optics Communications, 1995. **114**(5-6): p. 399-405.
57. Runge, P.K., *Experimental 50 Mb-S Fiber Optic Pcm Repeater.* Ieee Transactions on Communications, 1976. **24**(4): p. 413-418.
58. N. Subrahmanyam, B.L., *A textbook of Optics*. 2004, New Dehli: S Chand & Company Ltd.
59. Jeunhomme, L. and P. Lamouler, *Inter-Modal Dispersion Measurements and Interpretation in Graded-Index Optical Fibers.* Optical and Quantum Electronics, 1980. **12**(1): p. 57-64.
60. Miya, T., et al., *Ultimate Low-Loss Single-Mode Fiber at 1.55 Mu-M.* Electronics Letters, 1979. **15**(4): p. 106-108.
61. *Research Briefing 1987 for the office of science and technology policy, the national science foundation.* 1988, Washington D.C.: National Academy Press.
62. Koike, Y., *High-Bandwidth Graded-Index Polymer Optical Fiber.* Polymer, 1991. **32**(10): p. 1737-1745.
63. Okonkwo, C.M., et al., *Recent Results From the EU POF-PLUS Project: Multi-Gigabit Transmission Over 1 mm Core Diameter Plastic Optical Fibers.* Journal of Lightwave Technology, 2011. **29**(2): p. 186-193.
64. Ali, M.A., et al., *Performance of Erbium-Doped Fiber Amplifier Cascades in Wdm Multiple-Access Lightwave Networks.* Ieee Photonics Technology Letters, 1994. **6**(9): p. 1142-1145.
65. Sun, Y., et al., *Optical fiber amplifiers for WDM optical networks.* Bell Labs Technical Journal, 1999. **4**(1): p. 187-206.

66. Sun, Y., *Optical amplifiers for next generation WDM optical, communication networks.* 1999 Sbmo/Ieee Mtt-S International Microwave and Optoelectronics Conference, Proceedings, Vols 1 & 2, 1999: p. 349-349.

67. Mukai, T., Y. Yamamoto, and T. Kimura, *Optical Amplification by Semiconductor-Lasers.* Semiconductors and Semimetals, 1985. **22**: p. 265-319.

68. Saitoh, T. and T. Mukai, *1.5 Mu-M Gainasp Traveling-Wave Semiconductor-Laser Amplifier.* Ieee Journal of Quantum Electronics, 1987. **23**(6): p. 1010-1020.

69. Brosson, P., et al., *Design and Realization of High-Gain 1.5 Mu-M Semiconductor Tw Optical Amplifiers.* Electronics Letters, 1987. **23**(6): p. 254-256.

70. Akbar, J., et al., *High average power (200 mW) 40 GHz mode-locked DBR lasers with integrated tapered optical amplifiers.* 2012 Conference on Lasers and Electro-Optics (Cleo), 2012.

71. Akbar, J., *High Power Mode Locked lasers, Monolithically Integrated with Semiconductor Optical Amplifiers*, in *School of Engineering*. 2012, University of Glasgow: Glasgow. p. 162.

72. *Towards the Passive All-Optical Network.* Electronics & Wireless World, 1989. **95**(1644): p. 1013-1013.

73. Hill, A.M., et al., *An Experimental Broad-Band and Telephony Passive Optical Network.* Globecom 90 - Ieee Global Telecommunications Conference & Exhibition, Vols 1-3, 1990: p. 1856-1860.

74. Hilbk, U., et al., *High capacity WDM overlay on a passive optical network.* Electronics Letters, 1996. **32**(23): p. 2162-2163.

75. Mcgregor, I.M., G.J. Semple, and G. Nicholson, *Implementation of a Tdm Passive Optical Network for Subscriber Loop Applications.* Journal of Lightwave Technology, 1989. **7**(11): p. 1752-1758.

76. Senior, J.M., D.J. Ablitt, and D.W. Faulkner, *Passive Optical Network Performance with Tdm and Atm.* Broadband Networks: Strategies and Technologies, 1995. **2450**: p. 564-569.

77. Lin, C., *Broadband Optical Access Networks and Fiber-to-the-Home: Systems Technologies and Deployment Strategies*. 2006.

78. VanderPlas, G., et al., *Demonstration of an ATM-based Passive Optical Network in the FTTH trial on Bermuda.* Globecom '95 - Ieee Global Telecommunications Conference, Vols 1-3, 1995: p. 988-992.
79. Kim, G.Y. and J.H. Kim, *Wavelength Division Multiplexing-Passive Optical Network based FTTH field trial test.* Journal of the Optical Society of Korea, 2007. **11**(3): p. 101-107.
80. Park, S.J., et al., *An evolution scenario of a broadband access network using R-SOA-Based WDM-PON technologies.* Journal of Lightwave Technology, 2007. **25**(11): p. 3479-3487.
81. Marmur, O. and E. Shraga, *GPON - The next big thing in optical access networks.* Apoc 2003: Asia-Pacific Optical and Wireless Communications; Network Architectures, Management, and Applications, Pts 1 and 2, 2003. **5282**: p. 199-209.
82. Wilkinson, S.T., *GPON design gives it greater efficiency.* Laser Focus World, 2008. **44**(11): p. 11-11.
83. Baca, R. and M. Zuhdi, *Technological challenges to G-PON operation.* 2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference, Vols 1-8, 2008: p. 782-788.
84. Jain, S., et al., *World's First XG-PON Field Trial.* 2010 Conference on Optical Fiber Communication Ofc Collocated National Fiber Optic Engineers Conference Ofc-Nfoec, 2010.
85. Azim, M.M.A., et al., *A new hybrid architecture for Optical Burst Switching Networks.* High Performance Computing and Communications, Proceedings, 2005. **3726**: p. 196-202.
86. Bende, A.B., *Design and implementation of optoelectronic interfaces for high-speed burst-mode transmissions.* Journal of Vacuum Science & Technology B, 2000. **18**(4): p. 1962-1966.
87. Papadimitriou, G.I., M.S. Obaidat, and A.S. Pomportsis, *Advances in optical networking.* International Journal of Communication Systems, 2002. **15**(2-3): p. 101-113.
88. Thao, S., et al., *Direct carrier frequency compensation in burst mode satellite communication.* Globecom'99: Seamless Interconnection for Universal Services, Vol 1-5, 1999: p. 2244-2248.

89. Chen, Y., C.M. Qiao, and X. Yu, *Optical burst switching: A new area in optical networking research.* Ieee Network, 2004. **18**(3): p. 16-23.
90. Baldine, I., et al., *JumpStart: A just-in-time signaling architecture for WDM burst-switched networks.* Ieee Communications Magazine, 2002. **40**(2): p. 82-89.
91. Baldine, I., et al., *Just-in-time optical burst switching implementation in the ATDnet all-optical networking testbed.* Globecom'03: Ieee Global Telecommunications Conference, Vols 1-7, 2003: p. 2777-2781.
92. Yang, X.L., et al., *BM-VF-SBD: An efficient data channel scheduling algorithm to support QoS for optical burst switching networks.* Content Computing, Proceedings, 2004. **3309**: p. 120-130.
93. *GPON Standard:*. Available from: http://www.itu.int/rec/T-REC-G.984.1-200803-I/en.
94. Nesset, D., et al., *Extended reach GPON using high gain semiconductor optical amplifiers.* 2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference, Vols 1-8, 2008: p. 657-659.
95. Khlifi, Y., et al., *Optical packet and burst switching node architecture: Modeling and performance analysis.* ConTEL 2005: Proceedings of the 8th International Conference on Telecommunications, Vols 1 and 2, 2005: p. 507-514.
96. Duser, M. and P. Bayvel, *Analysis of a dynamically wavelength-routed optical burst switched network architecture.* Journal of Lightwave Technology, 2002. **20**(4): p. 574-585.
97. D. Hood, E.T., *Gigabit-capable Passive Optical Networks*. Technology & Engineering. 2012: John Willey & sons.
98. Hall, R.N., et al., *Coherent Light Emission from Gaas Junctions.* Physical Review Letters, 1962. **9**(9): p. 366-&.
99. Numai, T., *Fundamentals of Semiconductor Lasers*. 2004: Springer-Verlag, New York. 259.
100. Baranov, A.T., Eric, *Semiconductor lasers: Fundamentals and applications*. France: Woodhead Publishing, University Montpellier 2.
101. Harry J. R. Dutton, *IBM Understanding Optical Communication.* 1998.

102. Hayashi, I., et al., *Junction Lasers Which Operate Continuously at Room Temperature.* Applied Physics Letters, 1970. **17**(3): p. 109-&.

103. Koch, W.W.C.a.S.W., *Semiconductor-Laser Fundamentals*. 1999, Berlin: Springer.

104. B. E. A. Saleh, M.C.T., *Fundamentals of Photonics*. 1991, New York: John Wiley & Sons, Inc.

105. Sze, S.M., *Physics of Semiconductor Devices*. Second Ed. ed. 1981, New York: John Wiley and Sons.

106. Kressel, H., et al., *Heterojunction Laser-Diodes for Room-Temperature Operation.* Optical Engineering, 1974. **13**(5): p. 416-422.

107. G.P. Agrawal, a.N.K.D., *Long Wavelength Semiconductor Lasers*. 1986, New York: Van Nostrand Reinhold.

108. Michael Bass, C.D., Jay Enoch, Vasudevan Lakshminarayanan, Guifang Li, Carolyn Macdonald, Virendra Mahajan, Eric Van Stryland, *Handbook of Optics, Third Edition Volume II: Design, Fabrication and Testing, Sources and Detectors, Radiometry and Photometry*. 2010, New York: McGraw-Hill, Inc

109. Connelly, M.J., *Semiconductor Optical Amplifiers*

2002: Kluwer Academic Publishers.

110. Cox, J.T. and G. Hass, *Antireflection Coatings for Germanium and Silicon in the Infrared.* Journal of the Optical Society of America, 1958. **48**(10): p. 677-680.

111. Kelly, A.E., et al., *Polarisation insensitive, 25dB gain semiconductor laser amplifier without antireflection coatings.* Electronics Letters, 1996. **32**(19): p. 1835-1836.

112. Michie, C., et al., *Polarization-insensitive SOAs using strained bulk active regions.* Journal of Lightwave Technology, 2006. **24**(11): p. 3920-3927.

113. Wang, Z.T.U.o.D., STC Technology Ltd. ; Farre, J. ; Mikkelsen, B. ; Eskildsen, L., *High Performance 10' Angle-Facet Laser Amplifiers* in *Semiconductor Laser Conference*. 1990. p. 108-109.

114. Michie, C., et al., *An adjustable gain-clamped semiconductor optical amplifier (AGC-SOA).* Journal of Lightwave Technology, 2007. **25**(6): p. 1466-1473.

115. Soto, H., D. Erasme, and G. Guekos, *Cross-polarization modulation in semiconductor optical amplifiers.* Ieee Photonics Technology Letters, 1999. **11**(8): p. 970-972.

116. Bachmann, M., et al., *Polarisation-insensitive clamped-gain SOA with integrated spot-size convertor and DBR gratings for WDM applications at 1.55 mu m wavelength.* Electronics Letters, 1996. **32**(22): p. 2076-2078.

117. Davey, R.P., et al., *Long-Reach Passive Optical Networks.* Journal of Lightwave Technology, 2009. **27**(1-4): p. 273-291.

118. Michie, C., et al., *Reach extension of Passive Optical Networks using semiconductor optical amplifiers.* Icton 2008: Proceedings of 2008 10th Anniversary International Conference on Transparent Optical Networks, Vol 1, 2008: p. 194-197.

119. Ennser, K., M. Zannin, and S. Taccheo, *Extending Reach of Passive Optical Networks through Optical Amplification.* Icton: 2009 11th International Conference on Transparent Optical Networks, Vols 1 and 2, 2009: p. 849-852.

120. Leng, L.F. and T. Le, *A Raman amplified GPON reach extension system using parameters of a deployed fiber.* Optics Express, 2012. **20**(24): p. 26473-26479.

121. Davey, R.P., et al., *DWDM reach extension of a GPON to 135 km.* Journal of Lightwave Technology, 2006. **24**(1): p. 29-31.

122. McGough, J., *Semiconductor optical amplifiers to extend the reach of passive optical networks*, in *Electronic & Electrical Engineering*. 2013, University of Glasgow: Glasgow. p. 155.

123. Taylor, E.R.M., et al., *Thulium-doped tellurite fiber amplifier.* Ieee Photonics Technology Letters, 2004. **16**(3): p. 777-779.

124. Nishida, Y., et al., *Development of an efficient praseodymium-doped fiber amplifier.* Ieee Journal of Quantum Electronics, 1998. **34**(8): p. 1332-1339.

125. Laperle, P., et al., *Yb-doped LMA triple-clad fiber for power amplifiers - art. no. 645308.* Fiber Lasers IV: Technology, Systems, and Applications, 2007. **6453**: p. 45308-45308.

126. Lin, J.M., W.J. Ho, and C.Y. Li, *Dynamic Characterization of EDFA Based on ASE Selective-feedback and Gain-clamping Techniques.* Piers 2011 Suzhou: Progress in Electromagnetics Research Symposium, 2011: p. 922-925.

127. Summerfield, M.A. and R.S. Tucker, *Optimization of pump and signal powers for wavelength converters based on FWM in semiconductor optical amplifiers.* Ieee Photonics Technology Letters, 1996. **8**(10): p. 1316-1318.

128. Singh, Y.N., *Studies on Placement of Semiconductor Optical Amplifiers in Wavelength Division Multiplexed Star and Tree Topology Networks*, in *Electrical Engineering Department*. 1996, Indian Institute of Technology: Dehli. p. 133.

129. Holtmann, C., et al., *Monolithically integrated gain-clamped semiconductor optical amplifier exploiting Mach-Zehnder interferometer configuration.* 22nd European Conference on Optical Communications, Proceedings, Vols 1-6, 1996: p. C199-C202