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Design & Simulation of Integrated Semiconductor Optical Amplifier-Modulator and its use in Wavelength Division Multiplexing Passive Optical Access Networks

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ABSTRACT

Optical Access Networks are expected to become the dominant method for providing the broadband bandwidth in the last mile. DWDM though a standard for long haul transmission is not an automatic choice in the cost sensitive & star type distribution access networks. This severely limits the bandwidth capacities that can be achieved in the last mile to serve the next generation of services. In this work we study an integrated semiconductor optical amplifier modulator. We then use this SOAM to design a loop-back based passive optical network. The optical network is evaluated & simulated to demonstrate the feasibility of DWDM in access networks based on the ITU-T guidelines for optical access networks.
ACKNOWLEDGMENT

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I would also like to thank my parents, my brother & sister whose constant source of encouragement was instrumental in completing the research work.

To,

My family

&

Memory of Ravindranath Dantu
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1. Introduction

Over the past two decades there has been an exponential growth in information exchange. This information exchange requires transporting of data over various lengths of distances ranging from a few meters to thousands of Km at data rates ranging from a few Kbps to a few Tbps. Conventionally various transport networks have been developed for transport of data for different segments which were primarily classified by the distance they spanned.

The transport networks which span a few buildings are termed Local Area Networks and they are well served by ethernet networks and, more recently, by wireless networks. The networks which extend beyond local area networks and which span up to a few tens of km are termed access or edge networks. Conventionally this network has employed different technologies to deliver different services. These included copper loop in the last 3-5km from a local office to the subscriber. Networks which extend beyond access networks and up to a hundred Km are termed Metropolitan Area Networks. Traditionally these included trunk lines which interconnected several local offices or nearby cities. The networks which connect cities and continents are termed Wide Area Networks.

Optical networks have become the undisputed choice to carry data across vast distances owing to the distances they can cover, huge bandwidth and ease of maintenance. Several advances which include wavelength division multiplexing, improvements in optical fibers and various optical components have helped achieve the high bandwidth and the capacity for information transport across vast distances. With
mature optical technologies available for these long haul systems and with increasing demand for bandwidth in metropolitan area and access networks, the optical transport systems are slowly being used in these networks too.

Traditionally access or edge networks provide various services which include analog standard telephony & cable TV. The traditional services have different media to deliver different services and each of these have been further developed to also support the new digital services like internet access and various other services. The rapid growth of digital data communication, the bandwidth required of new internet based services and the planned future digital services require high channel bandwidth in access networks in Metropolitan Area Networks. The demand for multi-media applications and the de-regulation of communications require a network medium that does not tie the delivery of specific type of service to a specific type of medium. This requires converged networks that integrate voice, video and data services.

An ideal converged broadband access network should provide a multitude of bit-rates and a multitude of services including the standard telephony services (POTS). Such a network is essential in modern business operations with requirements like High speed inter-net access, cable services, video on demand, video conferencing, HDTV and also large band width leased lines for business users. Moreover the design of future proof network should allow its architecture to be easily scalable, easily accessible, easily maintained, resilient and economical.
Existing networks like copper loop which provides POTS (Plain Old Telephony) and CATV networking were further developed to provide digital services in the last decade. These developments intend to integrate all the services under one access network. The more successful of these solutions for access networks are Digital Subscriber Loop (DSL) & Hybrid Fiber Coax (HFC). These networks have inherent legacy problems like copper losses limiting the length of the connection to 3-6Km in the case of DSL and a highly asymmetrical network in the case of Hybrid Fiber Coax.

Highly mature optical network technologies can be applied to metropolitan area & access networks which can provide high bandwidths and are easily scalable & maintainable. Several solutions are proposed based on optical fiber for access networks and are commonly called Fiber To The Curb/Home/Cabinet (FTTx). However most of these solutions are star type network architectures from the central office to the subscriber and are not easily scalable & economical. Some of these solutions serve large industrial communities and medium sized enterprises reasonably well. These solutions are very expensive for residential & small business subscribers. The major challenge here is to move the optical fiber closer to the customer so that the infrastructure cost can be directly shared by many customers. With the advent of wavelength division multiplexing and improvements in passive optical components like semiconductor amplifiers and monolithic integrations of optical components, some of the proposed non workable solutions can be further developed to provide an ideal optical access or metropolitan area networks based on optical fiber.
1.1 Outline of the thesis

This work investigates the possibility of a converged optical access based on optical networking components which use wavelength division multiplexing and monolithically integrated optical components. This optical access network will provide high bandwidth, flexibility & scalability required of many of the futuristic services like video on demand, real time video conferencing for residential subscribers, high definition cable television & various other services.

This work considers hybrid optical access network architecture based on the loop-back method of optical transport. The loop back method is a way of transmitting upstream signals in passive optical networks. In this technique the wavelengths required for transmission of upstream signals are carried downstream from the central office and are then modulated at the remote location. This eliminates the technical complexity of generating wavelengths at the remote location. The disadvantage with this method in earlier approaches was that it required transmission of extremely high optical powers at the central office for the upstream signals. Also upstream transmitters at remote locations need to be placed at a wide range of distances from the central office and hence will lead to a wide range of received optical powers of the received optical signals. This requires high dynamic range optical receivers and puts a limit on the distances at which the remote optical networking units can be placed from the central office. Higher optical powers have the disadvantage of causing cross talk between neighboring wavelengths. The high optical input power of upstream wavelengths required by the loop back method can be mitigated by using Monolithic Semiconductor Optical Amplifier Modulator. The
monolithic integration of the amplifier & modulator helps greatly to reduce the insertion losses and improve the noise factor and will be the key to achieving nearly ideal access networks.

In order to achieve the goals of a future proof access network, we first study potential monolithic semiconductor optical amplifiers-modulators. The first type of monolithic optical amplifier-modulator considered is based on optical gain/loss that can be achieved in the fabry-perot cavity. The dynamic behavior of these monolithic amplifier-modulators is modeled by extending the traveling wave model proposed for optical amplifiers. We then use these models to model & simulate an optical access network and study its feasibility.
2. Access Networks

Before the advent of new digital services, the copper cable star type network which provided POTS and Co-axial cable bus type uni-directional networking were the only means for delivering data to many subscribers of the access network. Both of these network media, which reach out to the subscribers, use analog transport. With the introduction of new digital services over the past decade these networks were required to provide different types of services ranging from analog standard telephony service to next generation high definition television. Though the ideal transport network necessary for transporting these new digital services like high speed internet & video conferencing etc is not one of these existing analog networks, to preserve the existing investment in infrastructure and also as a transition while the ideal access networks are developed, traditional networks were further enhanced to provide digital services. It is expected that ultimately optical access networks will replace these networks over the next decade. In this chapter, we will discuss existing access networks including those based on POTS and CATV.

2.1 Digital Subscriber Line (DSL) Access Network

The DSL access network is based on the existing POTS infrastructure, which uses twisted pair copper cable star type of network between the central office and the subscribers, analog telephony on this twisted pair copper uses a bandwidth of 4Khz and usually spans a range of up to 7-8Km. The earliest attempt to provide digital services over the POTS network used this bandwidth and analog modulation and demodulation techniques provided the digital data services, with bandwidths of up to 28-56Kbps downstream and 14kbps upstream. In order to provide more bandwidth to the subscribers
the digital subscriber lines used a 1 MHz spectrum above the POTS 4 KHz. This bandwidth was very lossy at the higher frequencies and can only be used effectively for very short distances than the 3-5Km span of the POTS network. Signals on the standard POTS twisted pair greatly attenuate with distance, limiting data rates that can be transmitted over the POTS cable. A DSL modem is placed at the subscriber end of the link and Digital Subscriber Line Access Multiplexers (DSLAM) are placed at the central office.

There are several variants of the DSLs. One of the most successful of DSL variant is ADSL (Asymmetric Digital subscriber line)[13]. An Asymmetric Digital subscriber line provides the best bandwidth on a traditional twisted copper line. ADSL modems inserted at either end of the twisted copper pair can have three types of channels between them, a POTS channel, a high bandwidth downstream simplex channel and a medium bandwidth duplex channel in addition to a duplex control channel. The POTS channel is isolated from the other channels by filters and is designed to provide uninterrupted telephony. In particular, ADSL uses 0-4KHz for POTS, 28.5–138 KHz for the upstream channel and 138–1104 KHz for the downstream channel.

![Figure 2-1: ADSL frequency spectrum allocation](image-url)
ADSL can provide data rates up to 6Mbps in the downstream and up to 640Kbps in the upstream direction. Practically, these data rates are much lower and a good service is offered only at data rates of 1.5Mbps downstream and 128Kbps upstream. Higher data rates of 6Mbps downstream are limited to distances less than 2.7Km (1.5 miles) from the central office. Data rates of 1.5Mbps downstream are practical up to distances of 5.5Km (2 miles).

Table 2.1: ADSL maximum possible data rates[13]

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>Wire Gauge (AWG)</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>24</td>
<td>5.5</td>
</tr>
<tr>
<td>1.5</td>
<td>26</td>
<td>4.6</td>
</tr>
<tr>
<td>6.1</td>
<td>24</td>
<td>3.7</td>
</tr>
<tr>
<td>6.1</td>
<td>26</td>
<td>2.7</td>
</tr>
</tbody>
</table>

The key limitation of DSL is its distance from the subscribers in providing a high bandwidth. xDSL technologies can provide good bandwidths when the data needs to be transferred over short distances such as 300m - 1km. These variants can provide data rates of up to 13Mbps DS and 1.5Mbps US in the 1km case depending on the quality of the cable. DSL has advantages over fiber in terms of enormous flexibility of providing service provisions at the subscriber end. Fiber access networks can exploit this property to provide an ideal hybrid solution.

2.2 Cable based Access network

Another traditional network, which also has extensive infrastructure, is CATV (Community Antenna TV) network. Primarily the CATV network is a tree or a bus type broadcast network in which the signal is amplified many times before it reaches the subscriber. This network is built-up with coaxial cable of 24 or 26 gauge wires. It uses
the spectrum from 40-450Mhz for broadcasting video. CATV also uses a multimode fiber for the initial few miles of the network to carry the broadcast video signals, which is then broadcast on copper network. This variation has been widely adopted and is popularly called Hybrid Fiber Coax (HFC)

HFC is terminated at the subscriber end by a cable modem and the other end by a fiber node. Each fiber carries OC12 or OC48 channels to the CO where it is terminated by CMTS (cable modem termination system). Each fiber node serves about 500-1000 users. The amplifiers in the branches are replaced by bi-directional units to allow upstream transmission. There are currently two different standards proposed for HFC access one by IEEE 802.14 and another popular one by DOCSIS[14].

The CATV bandwidth is divided into three bands 5-50 MHz upstream digital channels, 50-450 MHz 6 MHz analog channels and 450-750 MHz downstream digital channels for providing digital access over the analog network. In the downstream direction data is broadcast at data rates up to 27Mbps with 64/256 QAM and forward error correction. In the upstream direction, users have to share the channel and the transmission window and collision avoidance is set by head-end control. Upstream bit rates from 786Kbps to 5.12Mbps are possible with quadrature phase shift keying and time division multiplexing. The upstream burst is transmitted on a number of shared channels between 5 and 42 MHz and in future this can be expanded to the 108-174 MHz range.
The primary limitation of HFC is that its bandwidth is shared by a large number of users. This is especially severe in the upstream direction where the bandwidth is to be shared between several hundred users.

2.3 Passive Optical Networks

Many optical networks solutions had been proposed for optical access. The most bandwidth intensive solution is the FTTH (fiber to the home) where every house is connected to the central office by an optical fiber. Clearly, this is not scalable for very high penetration rates and not economical for low penetration rates. But it offers many advantages of large downstream and upstream bandwidths, secure communication and ease of maintenance. FTTC (Fiber to the Curb) is proposed in which the fiber is taken to the roadside, and all the equipment and bandwidth is shared and then distributed as required to the subscribers. This solution requires optical networking equipment that is temperature sensitive to be placed outside the plant. This substantially increases maintenance complexities and costs. The advent of passive optical components has given new thrust to the FITL (Fiber in the Loop) implementations and a few viable architectures based on PON (Passive Optical Networks) were proposed and have been demonstrated.

The local loop is the network between the central office and the subscribers. The optical node at the central office is commonly referred to as Optical Line Terminal (OLT). At the subscriber end these are terminated by Optical Networking Units (ONU). The network between them is referred as an Optical Distribution Network (ODN).
Typically a single line terminal (OLT) serves a large number of networking units (ONU). The distribution network (ODN) can be either a star or a ring type of network or a combination of both. The optical signals in the downstream can be de-multiplexed directly at the ONU or further carried over a different fiber to the ONU after being de-multiplexed. The bandwidth is further distributed from the ONU to the subscribers.

![Hybrid Optical Access Network](image)

**Figure 2-2: Hybrid Optical Access Network**

For the Fiber in the Loop passive optical networks (PON) offers the advantage of not requiring temperature sensitive active components and remote power, thereby substantially reducing the issues of remote power ups and maintenance. The de-multiplexing (downstream) or multiplexing (upstream) is done optically and passively. The main advantage of the PON is that it is future safe over other technologies due to the large bandwidth of optical fiber. With passive components the system can be upgraded
for higher bandwidth services without much change to the existing network. Changes are mostly made at the line terminal (OLT) and only for those subscribers requiring change. At the line terminal (OLT) the light sources and receivers are shared by many subscribers which greatly reduce the total system cost.

In PON multiplexing from information of different subscribers is done passively. Therefore an access technique that prevents collision of information of different subscribers is required. These techniques can be broadly divided into three categories, TDMA (Time Division Multiple Access), WDMA (Wavelength Division Multiple Access) and SCMA (Sub-carrier Multiple Access). In TDMA collision is avoided by the access protocol which assigns time slot or cells to each subscriber. Only the assigned subscriber is allowed to transmit in that particular time slot. In WDMA a number of different wavelengths are used along with wavelength assignments to the user, to avoid collision of data. In SCMA an electrical signal with data at different frequencies for each subscriber is modulated onto the light wave for avoiding access collision. PON are generally categorized based on these access methods. This results in mainly three types of access PON.

- TDM based PON
- SCM based PON.
- WDM based PON

2.3.1 TDM based PON

In the TDMA based approach, access to different subscribers is provided by reservation of time slots in a frame or by allocation of cells for transmission. This
reservation of time slots can both be fixed and dynamic. A number of reservation algorithms have been proposed. To support a particular reservation system appropriate MAC protocol has to be developed.

PLANET (Photonic Local Access Network)[16,18] which is a European system uses TDMA in its passive optical broadband access network. The PLANET access network is designed for a span of 100 km consisting of 90km of feeder length and 10km of drop section and for a very high splitting factor of 2048. The transport system is based on ATM cells in TDMA slots. A downstream bit rate of 2.5Gbps is distributed to the ONU (Optical Networking Units) utilizing the TDMA protocols. A TDMA protocol is also used to share the 311mbps upstream bit rate. The large span of the fiber from the ONU (optical networking unit) to the OLT (optical line terminal), optical amplifiers have to be used in the fiber network.

2.3.1.1 Architecture of PLANET

The aim of the European PLANET (Photonic Local Access Network) is to develop a cost-effective full services optical access network based on super PON (super Passive Optical Networks). The typical distance between the Optical line terminal (OLT) and an ONU (optical networking unit) is 100km. The feeder length of 90km contains two drops of fiber each with 45 km length and an EDFA amplifier at the end of each drop. At the Line Termination the electrical to optical transceiver operates at 1550nm and 2.5Gbps. The transmitter has an integrated isolator and the typical output power is 0 dBm. At the end of each feeder drop the signals are amplified by EDFAs in the downstream direction and semiconductor optical amplifiers (SOA) in the upstream direction. Downstream and
upstream transmissions are coarse wavelength multiplexed at 1.55um and 1.31um. At the end of the feeder drop the fiber is connected to an Amplifier Splitter (AS) where bit stream is power split in the ratio of 2:16. The initial part of 2:1 of 2:16 provides the required redundancy for narrow band services and leased lines.

Figure 2-3: Architecture of the European Photonic Local Access Network (PLANET)

Further down the distribution at around 8km Splitter Units (SU) with ratios of 1:128 are used. The downstream bit rate of 2.5 Gbps is formed by bit multiplexing four 622Mbps channel streams. Each ONU (optical networking unit) locks to one of the four streams and an additional optional one for carrying distributive services. The gigabit clock circuitry is limited to first demultiplexer component. ONUs (optical networking units) may be located in a fiber to the home/premises (FTTH/P) configuration or in a premises unit concentrating several subscribers (FTTC) with a very high rate digital subscriber loop (VDSL) copper drop to the network termination (NT) in each home.

The proposed SuperPON uses TDMA (Time Division Multiple Access) for sharing the bandwidth between users. TDMA (Time Division Multiple Access) slots are accommodated by a single ATM cell. The broadband services present a variety of rates
and strong temporal fluctuations. These coupled with strict cost, make the efficiency and flexibility of ATM-cell based transport a very good choice. This ATM based approach is very similar to the more conventional APON systems standardized by the FSAN initiative. The most important difference between a conventional APON and SuperPON is the use of optical amplifiers (OA)

The transceiver at the ONU (optical networking unit) enables upstream transmission of 311Mbps at 1.31μm and includes the downstream part of a 2.5Gbps receiver. The laser transmitter proposed for the upstream does not contain any thermo controllers to keep the cost of equipment down. Output powers of more than 10mW at 85°C are obtained. Upstream optical amplification is complicated by the noise funneling effect. In the upstream direction the optical splitters act as signal combiners. This also results in amplified spontaneous noise because several parallel optical sources are being combined, severely degrading the SNR ratio of the signal. Hence this network employs burst mode operation of parallel optical amplifiers and the amplifiers are switched on only when they need to amplify an ATM cell in the TDMA slot and turned off otherwise.

The speed required for this switching requires very short time constants. SOA’s (semiconductor optical amplifier) with very fast switching time constants are more suited for this upstream amplification than the EDFA's which have very slow gain dynamics. The switch able SOA’s(semiconductor optical amplifier) offer the possibility of cell to cell automatic gain, thereby helping reduce the dynamic gain required by the
receiver. This functionality is achieved by microprocessor control of the SOA (semiconductor optical amplifier). The introduction of microprocessors greatly increases the system operational complexity. Different amplifiers for the downstream and upstream directions require coarse wavelength de-multiplexers which increase the system complexity and cost.

2.3.2 SCMA

In SCMA the base band signal of a subscriber modulates an electric carrier with a frequency unique to each subscriber in a particular modulation format[17]. All the frequency modulated signals are then multiplexed to form a single carrier. This carrier can also be up-shifted in frequency in some cases. The final electric carrier is then used to modulate the light wave. Since the light-wave is the main carrier, the electric carrier is called the sub-carrier. These light waves are multiplexed passively in the PON. The optical receiver in the central office converts them back into electrical signals, whose spectrum has distinct frequency bands and these are filtered in the electrical domain to produce the individual subscriber signals.

This technique uses central control for transmission of data and hence suffers a very big disadvantage for transmission in upstream direction. This technique is ideally suited for downstream broadcasting of cable channels on the passive optical network

2.3.3 WDMA based PON

There are many local access experimental demonstrations using WDMA in the last mile. Among the first well known WDM-PON's in the literature were RITE-Net and
LAR-Net[8, 9], both proposed by AT&T's researchers and are essentially FTTH (fiber to the home) networks. Both the architectures have been realized and experimentally demonstrated. Both RITE-Net and LAR-Net architectures use waveguide grating routers (WGR) in one single remote node. The wave-guide router routes a continuous set of equally spaced frequency bands to different output ports. The WGR (waveguide grating router) has the important property of multiplexing equally spaced frequencies into a single channel when used in the reverse direction. These architectures form the basis of most WDM based local access implementations.

![Figure 2-4: Architecture of LAR-Net](image1)

![Figure 2-5: Architecture of the RITE-Net](image2)
Equally spaced optical channel wavelengths are transmitted in the downstream direction. These channels are routed to other further downstream fibers with the WGR (waveguide grating router) in a star type of network. The other end of the fiber drop is connected to the ONU (optical networking unit). WGRs (waveguide grating routers) offer an elegant solution for broadcast services in the downstream direction. A wideband optical source modulated with the data is used to transmit the broadcast data. The WGR routes this wideband channel into equally spaced wavelengths each available at a different port. In LAR-Net one single fiber is dedicated to every subscriber. The downstream traffic is transmitted employing the 1550nm optical window (coarse WDM Bi-directionality), while for upstream traffic the wavelengths at 1300nm are used. In RITE-Net, the two fibers are dedicated to every subscriber, each able to carry traffic in one direction. (space division bi-directionality). These architectures have two main limitations. They are not scalable for a large number of users once the network is laid out. There is a limited number of users because of WGR (Wavelength grating router) size.

A way of addressing the issue of scalability is to bring fiber to the cabinet/curb and let many users share a fiber from the line terminal (OLT) to the networking unit (ONU) at the curb. Towards this goal many vendors and service providers have joined to establish a common standard for such architecture and establish the economies of scaling. These companies work together as a full services access network (FSAN) consortium and make recommendations which have been incorporated in the
International Telecommunication Standard (ITU) G.983.1[19] It incorporates WDM only as CWDM.

**Figure 2-6: Wavelength division based Passive Optical Network**

### 2.3.3.1 APON

APON uses WDM or passive power splitting for downstream transmission and uses power combining in the upstream direction. WDM for downstream is proposed only as an upgrade to the power splitting. A single transceiver in the OLT (optical line terminal) of the central office connects with multiple ONUs (optical networking units). The downstream signals are transmitted by a single laser in power splitting configuration and a multi-wavelength source in WDM case. The supported downstream bit rate is 155.52mbps or 622.08Mbps. These downstream signals are passed through the power splitter. The minimum supported power splitting ratio is either 1×16 or 1×32. Signals originating in the ONU (optical networking unit) are transmitted upstream using 1.3µm Fabry-Perot lasers to the power splitter. The upstream and the downstream signals are carried over a single fiber. Traffic is carried in ATM cells in both directions, which permits dynamic allocation of bandwidth and hence the available bandwidth can be efficiently used. The average downstream bit rate available per ONU (optical
networking unit) is 10 - 39 Mb/s. The upstream bandwidth from each ONU (optical networking unit) is held at 10 Mbp/s. These bandwidths of each ONU (optical network unit) can be further shared between subscribers with the copper access technologies like DSL & Cable access.

![Diagram of Power Splitting Passive Optical Network]

**Figure 2-7: Power Splitting Passive Optical Network**

Since the Power Splitting PON (PSPON) splits the power of the channel, the PSPON (power splitting PON) must be able to operate over a range of outside plant losses. Two classes of loss are defined. For class B, the loss ranges between 10 and 25 dB. Class C losses range from 15 to 30 dB. Additional losses will be present due to splices, CWDM's, and in the ONU (optical networking unit) and OLT (optical line terminal). OLT (optical line terminal) might receive different ATM cells with different powers that have suffered different plant losses. This differential network distribution loss in the upstream direction becomes the dynamic range of the receiver in the OLT (optical line terminal). This requirement is fixed at 22 dB. This includes a healthy margin to allow for output power variation of the transmitters and to permit interoperability of transmitters and receivers from different vendors. Another specification is the differential path length for a single PON which is set at 20km. Another issue is that the equipment has to operate outdoors and hence must operate over
a temperature range of -40°C to +85°C and indoor equipment in a range of 0-60°C. These cause large variation in the received power and are the source of large differential path loss.

Downstream transmission in a WDM-PON requires a multi wavelength source at the OLT (optical line terminal) and a wavelength de-multiplexer as a branching device. There are several de-multiplexing devices. A passive optical router can operate over multiple free spectral ranges within the fiber-optic transmission windows. This adds flexibility by permitting extra wavelengths to be added as an upgrade. Routers are currently expensive, but the cost is expected to come down as they use the same manufacturing technology as power splitters.

Temperature changes cause the passbands of the router to drift with temperature typically at a rate of about 0.011 nm/°C. In a WDM-PON system with no outdoor temperature control this can cause the passbands to drift nearly 1.4 nm over the operating range. Current WDM systems use routers with 100 or 200 GHz channel spacing, corresponding to 0.8 or 1.6 nm in the 1.55 μm wavelength window. Thus Temperature changes have major implications for the operation of a WDM-PON. Routers with much-reduced temperature dependence are being demonstrated in the laboratory. To overcome these effects the temperature of a router needs to be tracked and the wavelengths changed accordingly for both upstream and downstream laser sources. For upstream laser sources, this requires distributed control which is not feasible outside the plant conditions. Another strategy is to set and forget very wide channel spacings, so that
the wavelengths from the multi-wavelength source remain within the router pass-bands throughout the entire temperature range experienced by the router. This option severely reduces the bandwidth that can be used with multiple wavelengths.

The wavelength tuning in the downstream direction is much simpler. With modest tracking and control, a channel spacing of 400 GHz is easily achieved which allows about 16 channels in the 1.55µm wavelength C-band window. The multi-wavelength sources can be either 16 discrete lasers or an integrated multi-wavelength source. In the case of discrete lasers very good control of wavelengths is achieved by and constantly fine tuning with some sort of control. The Multi Frequency Laser has very good control of the channel spacings since the channel spacings are based on differential path lengths of the laser. With this device the wavelengths at a line terminal (OLT) can be tuned very easily by varying the single temperature parameter.

### 2.3.3.2 Multistage WDM-PON access networks

In recent WDM PON's, the de-multiplexing function implemented by waveguide grating routers (WGRs) has become the basic building block of WDM PON's. This passive wavelength routing component is also called an arrayed waveguide grating (AWG) and has been extensively studied[20]. It is fabricated with silica-on-silicon technology in integrated optics. The connectivity properties of a generic WGR (Wavelength grating router) can be described in a discrete two-dimensional domain, the two axes representing space and wavelength. WGR (Wavelength grating router) being a passive device is able to perform only space permutations. A channel in a generic WGR
(Wavelength grating router) is identified by two space co-ordinates which correspond to the input and output port number of a WGR (Wavelength grating router) through which the channel enters and leaves the device. The ports are numbered by a progressive integer. Optical signals entering from a given input \( i \) are routed to a particular output \( j \).

The WGR (Wavelength grating router) behaves like a periodic band-pass filter, its power transfer function having peaks repeated at a fixed wavelength interval called the free spectral range (FSR). The transfer function from the input port \( i + 1 \) to a given to a given output \( j \) has the same shape as the previous transfer function of input \( i \), but it is shifted on the wavelength axis by a wavelength interval \( \Delta \lambda \). A WGR (Wavelength grating router) is characterized by free spectral range \( FSR = M \Delta \lambda \), by a size factor \( M \) and a coarseness \( C \) which operates over a wavelength comb defined by

\[
\lambda(f) = \lambda_0 + (f - 1)\Delta \lambda
\]

and with space wavelength domain parameters \( (i, j, f) \) with \( (i, j) \in [1, M] \) then the routing function can be defined by

\[
j = 1 + \left( i - 1 + \left\lfloor \frac{f - 1}{C} \right\rfloor \right) \mod M
\]

A super passive optical network[10] is built by cascading \( k \) stages of WGRs (Wavelength grating router) with \( k > 1 \). In each stage \( N_k \) WGRs (Wavelength grating router) are connected to the outputs from the previous stage. In the final stage the outputs are connected to the ONU (optical networking units). These type of architectures can be subdivided into two classes depending upon the coarseness of the WGR (Wavelength grating router) in each stage, a Decreasing coarseness (DC) type and
increasing coarseness (IC) type. The DC type Super PON’s are not scalable, but IC type Super PON's have this property.

There are many disadvantages inherent in this architecture for access networks. The use of multistage WGRs (Wavelength grating router) introduces losses of approximately 6db per WGR. The losses due to WGRs (Wavelength grating router) become very substantial and require a very high power budget in the downstream. Also, this architecture, in the upstream mode suffers from the same limitations as other architectures. In fact WGR (Wavelength grating router) stages introduce extra losses in the upstream which are a big disadvantage.

2.4 Future Trends

There are many alternate proposals for implementing the PON access networks. In all these networks, the downstream solution provides a very large
bandwidth, and a high splitting factor. This is made possible by the ease with which light is transmitted at very high bit rates and on multiple wavelengths from the line terminal (OLT). Hence, a very large downstream bandwidth can be provided to all the subscribers. However, in all these solution the upstream bandwidth is very low. Typical total upstream bandwidth in most of the existing implementations does not exceed 300Mbps. This bottle-neck is due to the very complex task of generating stable multi-wavelengths from different sources placed in different locations in an ONU(optical networking unit) and constantly maintaining the channel spacings.

There are two main ways to increase the bit rate.

1. By transmitting at a higher bit rate, and
2. By transmitting on more than one wavelength.

The first option is not easily scalable with increases in the number of subscribers. Also for splitting factors of the order of 2048, this is prohibitively costly. The other option is to use WDM. This requires the availability of equally spaced channels. Two methods have been proposed to make available equally spaced channels, Loop-back and spectral splicing.

2.4.1 Loop Back method

In this option a portion of the downstream light is passed through a modulator at the ONU(optical networking unit) and then this modulated light is looped back to the line terminal (OLT). This looping back of transmission requires a high power laser source which is capable of meeting the loss budgets of both the upstream and downstream needs with necessary amplification in an upstream location.
Downstream signals can also be amplified, but require the amplifiers to be placed in each of the ONUs (optical networking units) in existing implementations. This also requires modulators in the transceiver part of the ONU. An additional disadvantage of the loopback method is the requirement of two fibers one each for upstream and downstream transmissions to avoid unacceptable levels of interference from coherent Raleigh backscattering.

2.4.2 Possible Improvements

The loopback method requires the availability of equally spaced channels. A simple scheme can be used to regenerate the wavelengths at the downstream demultiplexing point. The downstream signal is power split and fed into a fabry-perot cavity, with appropriate reflection co-efficient.

This power output from the passive fabry-perot cavity is fed into an EDFA. The power at the end of the EDFA is again split and a part is fed back into the cavity. This scheme enables regeneration of all the wavelengths in the 1.55um window.

These wavelengths can either now be modulated and fed back into the wavelength grating router and routed to ONU’s or demultiplexed and coupled into the downstream signals. The wavelengths are either coupled or routed in such a way that minimum possible channel spacings between the downstream wavelengths and those for upstream transmission are always maintained. At the ONU (optical networking unit) the signals are demultiplexed by a narrow band filter and input to the receiver and modulator. Currently low cost modulators without amplification are available only in laboratories. An alternative to this is to do 3R regeneration at the downstream demultiplexing point. i.e., low speed Lasers/LED are used for transmitting the data from the ONU (optical
networking unit) to the demultiplexing point. At this point opto-electro conversion of data is done and data from different ONUs (optical networking units) is multiplexed and transmitted by modulators on one of the available wavelengths. This requires very few modulators (equal to the number of wavelengths) and the cost can be easily shared over a large number of subscribers.
3. Integrated Semiconductor Optical Amplifier Modulator (SOAM) modeling

Access and edge networks quite often require the laser transmitters be placed outside the plant location and at various locations many of which transmit wavelengths on a single fiber. This can significantly reduce the density of wavelengths that can be used on access and edge networks. This study examines ways to simplify problems of continuous wavelength tuning, tracking and synchronization required between several transmitters at various locations. These problems arise in upstream transmission of data with several laser transmitters placed outside the plant environment.

Many solutions have been proposed to alleviate such problems of these Loop back modulation at the remote end of un-modulated wavelengths transmitted by the optical line terminal (OLT) is one promising approach. Recent advances in semi-conductor optical amplifiers have made possible the use of these semiconductor optical amplifier devices in optical networks for optical amplification. This work evaluates this method of upstream transmission with an integrated semiconductor optical amplifier modulator.

3.1 The loop back network architecture

Metro and access networks, involve data communication between a central office and remote locations. They only spawn short distances easing the requirements on optical components. Practical topologies are achieved with star and ring type networks. Transmission from the central office to remote location is regarded as downstream propagation direction. Transmission from the remote location to the central office is regarded as upstream propagation direction. The use of several independent wavelength
sources at various locations limits the highly cost sensitive access networks to coarse wavelength division multiplexing in the upstream direction. In the downstream direction, it is possible for dense wavelength multiplexing because the wavelength source is located at a single place and in a controlled environment. Since only a single multi wavelength source is required for the entire downstream direction, the complexity, scalability, maintainability and cost of downstream transmissions are significantly less than that of the upstream case. The loop back method of upstream transmission significantly reduces the complexity associated with upstream transmission.

In the loop-back method for passive optical networks two different sets of wavelengths are allocated to upstream and downstream transmissions. The wavelengths required for upstream transmission are generated at the central office instead of a remote location. They are transmitted downstream as continuous wavelengths (un-modulated with data) to remote locations. At the remote end they are modulated with upstream data and transmitted in the upstream direction either on the same fiber or on a different fiber. Previous attempts to address the modulator at the remote end have shown issues with high insertion losses, polarization sensitivity and moderate gain at the remote end. They also require high transmission power from the central office and wide dynamic range photo receivers and can cause problems. Hence other architectures have been preferred for the loop back architecture. Recently, polarization sensitivity of semiconductor optical amplifiers has been improved to within 0.5dB[1]. This coupled with monolithic integration of the modulator with the amplifier has enabled the upstream wavelength
density to be greatly improved and the optical power required by the central transmitter to be greatly reduced.

3.2 Integrated Semiconductor Optical Amplifier Modulators (SOAM)

For use in access networks, two types of integrated semiconductor optical amplifiers with modulators are possible. Both types of devices essentially have the same structure for light amplification. They differ in the modulation schemes that they can be integrated with. Since optical amplification depends upon current biasing for the active region, the simplest integration of the modulator involves gain modulation via current bias modulation. Other integration of an SOA involves electro-absorption modulation based on Franz-Keldysh effect. The gain modulated integrated SOA-modulator will be described and modeled for use in access systems. Construction and modeling of other possible SOAM with electro-absorption modulation schemes was attempted but with limited success for use in loop-back method of passive optical network.

3.2.1 Design and Construction of the gain modulated SOAM

Semiconductor optical amplifiers use an In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$/Inp quaternary double hetero-structure scheme for light amplification in the 1.3-1.7nm region. Band gap energies for In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ lattice matched to InP range from 0.718ev to 1.347ev. The device structure is grown on a (001) oriented n-doped InP. A layer of In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ of the required thickness is grown using LPE. On top of In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ layer a shallow intrinsic InP or an intrinsic In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ ($\lambda_g \sim 1.3\mu$m) cladding layer is grown. The mesa structure is obtained by using optical lithography and a chemical etch. This is followed by a p-doped InP overgrowth and a p-doped In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ contact layer. A part of the p-doped InP region between the optical amplifier region and electro
absorption region is etched off to provide electrical isolation. To improve coupling efficiency the mesa structure is tapered in width at both ends. Very low reflectivity at both facets is achieved by a coating of antireflective material and also by waveguide tilting with respect to the length. When tilted waveguides are used, the reflected light does not couple back into the waveguide mode.

Integrated optical amplifier and modulator

Figure 3-1: Cross section of Semiconductor Optical Amplifier Modulator (SOAM)

Figure 3-2: Top view of the integrated SOAM

Figure 3-3: Cross section view of SOAM
3.2.2 Modelling of the Integrated SOA and Modulator

There are various models of different complexity for determining the static and dynamic behavior of semiconductor optical amplifiers. These models relate the internal physical variables (length, confinement factor, bandgap, temperature, current bias etc) of the amplifier to external observable and measurable parameters such as the output power, optical gain, gain saturation, noise and others. A very good simulation model is invaluable for the design and optimization of the device itself. Analytical techniques can be used to model a SOA, but they are usually applicable only over a narrow operating range and are not very accurate. Reasonable accuracy for a SOA model generally requires a numerical solution approach. Numerical solutions make fewer assumptions about the behavior of the SOA and are very useful for obtaining insights into the operation of the SOA. A numerical solution based on the wideband model for a buried ridge stripe SOA[2,5] is used to model the integrated semiconductor optical amplifier-modulator(SOAM). The SOA model reported in [2,5] is briefly described below.

The device structure of a buried ridge stripe SOA consists of an active region of width $w$, and thickness $d$. It has an amplifier active region length $L_a$, a modulator region of length $L_m$ and an isolation region of length $L_i$. The active region width $w$ at the ends is linearly tapered down to lithographic limit over the length $L_t$ to increase coupling efficiency into the fiber. The model considers optical amplification of group of $N_s$ wavelengths with frequencies $\nu_k (k = 1…N_s)$. The power input by the SOA into each wavelength is given by $P_{ink}$. The following assumptions are made in the model:

- The transverse variation of the photon and carrier density rates is neglected
The modulus squared of the amplitude of the traveling wave set equal to the photon flux in the direction of propagation

If \( N_{s_k}^+ \) is the number of photons in the positive direction of propagation and \( E_{s_k}^+ \) is the amplitude of the wave traveling in the positive direction then for each component wavelength \( k \), \( N_{s_k}^+ = |E_{s_k}^+|^2 \). Similarly for propagation in the negative direction, the photon density of the negative traveling wave is \( N_{s_k}^- = |E_{s_k}^-|^2 \). The input signal to the SOA is treated coherently since its transmission properties depend upon the frequency and phase of the individual frequency components. The wave amplitudes \( E_{s_k}^+ \) and \( E_{s_k}^- \) in the positive and negative directions satisfy the complex traveling wave equations,

\[
\frac{dE_{s_k}^+(z)}{dz} = \left( -j\beta_k + \frac{1}{2} \left( \Gamma g_m(v_k, n) - \alpha(n) \right) \right) E_{s_k}^+(z)
\]

(1)

\[
\frac{dE_{s_k}^-(z)}{dz} = \left( j\beta_k - \frac{1}{2} \left( \Gamma g_m(v_k, n) - \alpha(n) \right) \right) E_{s_k}^-(z)
\]

(2)

where \( \beta_k \) is the wave propagation constant and is given by \((2\pi n_{eq}v_k)/c\), \( \Gamma \) is the optical confinement factor, \( \alpha(n) \) is the propagation loss, \( g_m(v_k, n) \) is the optical gain at wavelength \( k \) with carrier density \( n \). For mathematical modelling, the amplitude of the light waves in each direction can be calculated by integrating on both sides. Integration of the real part gives the amplitude and the imaginary part the phase. The photon densities are calculated using

\[
N_{s_k}^+ = e^{\int \left( \Gamma g_m(v_k, n) - \alpha(n) \right) dl}
\]

(3)

and
subject to the boundary conditions,

\[ E_{s_k}^+(0) = (1-r_1)E_{e_k}^+(0) - r_1E_{s_k}^-(0) \]

\[ E_{s_k}^-(L) = -r_2E_{s_k}^+(L) \]

where \( r_1, r_2 \) are the Fresnel reflection coefficients at the input and output facets respectively and \( g_m(v_k, n) \) the optical gain at wavelength \( k \) with carrier density \( n \) is given by

\[ g_m(v_k, n) = \frac{c^2}{4\sqrt{2}\pi n_1^2 e^2 \tau v^2 \left( m_e + m_{hh} \right)^\frac{3}{2}} \left( \frac{2m_e m_{hh}}{\hbar(m_e + m_{hh})} \right)^\frac{1}{2} \sqrt{v_k - \frac{E_g(n)}{\hbar} \left( f_e(v_k) - f_c(v_k) \right)} \]

where \( c \) is the propagation velocity of light, \( n_1 \) is the refractive index of the active waveguide region, \( \tau \) is the radiative recombination coefficient, \( m_e \) and \( m_{hh} \) are effective masses and \( E_g(n) \) is the band gap energy as a function of carrier density. \( f_e(v_k) \) & \( f_c(v_k) \) are the Fermi-Dirac distributions for the conduction and valence bands respectively. The Fermi levels are calculated using Nilsson’s approximation [15]

\[ E_{f_c} = \frac{1}{kT} \ln \left[ 64 + 0.005524e \left( 64 + \sqrt{e} \right) \right]^{\frac{1}{2}} \]

\[ E_{f_c} = \frac{1}{kT} \ln \left[ 64 + 0.005524\delta \left( 64 + \sqrt{\delta} \right) \right]^{\frac{1}{2}} \]

where \( N_c, N_v \) are conduction band and valence band densities of states, respectively and \( n, p \) are electron and hole carrier densities. \( E_g(n) \) is the energy of the band gap in the presence of carriers and is given by \( E_g(n) = E_{g0} - eK_g n^{\frac{1}{2}} \) where \( K_g \) is the band gap shrinkage coefficient. The signal output power at the output facet is be given by
\[ P_{\text{out}} = \eta_{\text{out}} h \nu_k |E_{\text{out}}|^2 \]  
\[(10)\]

where \( \eta_{\text{out}} \) is the output coupling loss.

### 3.2.3 Modeling of Spontaneous Emission Noise

Spontaneous emission also gets amplified along with the intended signal if its frequency is in the gain region of the amplifier. Its presence reduces the useful carrier density and causes early onset of saturation. Since the spontaneous emission affects the signal mainly through the depletion of carriers, a different approach is used to model the effects of spontaneous noise. The model uses the following assumptions, which are verified later.

- The Amplifier has extremely low reflectivity’s, hence it acts like a traveling wave amplifier which will only couple insignificant power into the reflected waves implying very small gain ripple for resonant and anti resonant frequencies
- Depletion of the carriers can be calculated by the gain experienced by the forward and backward traveling waves and they need not be treated coherently
- The gain of the resonant frequencies is used to estimate the noise. Averaging the coherent signal over two adjacent cavity resonances is equivalent to treating the signal coherently.

The frequencies at which the gain is calculated to estimate the average noise are given by

\[ \nu_j = \nu_c + \Delta \nu_c + K_m \Delta \nu_m \]  
\[(11)\]

where, \( \nu_c \) is given by \( E_{go}/h \), \( \Delta \nu_c \) is added to make it a resonant frequency, \( K_m \) is a weighting numerical parameter used to decrease the simulation time and \( \Delta \nu_m \) is given by
\[ \Delta \nu_m = \frac{c}{2 \int_0^L n_{eq} \, dz} \]  

(12)

For spontaneous emission noise, the photon densities \( N_j^+ \) and \( N_j^- \) travel in positive and negative directions respectively in a particular TE or TM mode with a center frequency \( \nu_j \) and the rate equations,

\[
\frac{dN_j^+(z)}{dz} = \left( \Gamma g_m(\nu_j, n) - \alpha(n) \right) N_j^+ + R_{sp}(\nu_j, n) \\
\frac{dN_j^-(z)}{dz} = -\left( \Gamma g_m(\nu_j, n) - \alpha(n) \right) N_j^- + R_{sp}(\nu_j, n)
\]

(13)  

(14)

The expression for spontaneous emission rate is derived by comparing with the quantum mechanically derived expression of an ideal amplifier. Ideal amplifier assumes zero loss coefficient, zero facet reflectivity’s, zero coupling loss and a constant material gain coefficient \( g_m = g_m^j (>0) \) with no gain saturation,

\[ R_{sp}(\nu_j, n) = \Gamma g_m^j(\nu_j, n) K_n \Delta \nu_m \]  

(15)

The traveling wave power equations assume that all the spontaneously emitted photons within the spectral window \( K_n \Delta \nu_m \) experience the same gain that the photons at the resonance frequencies do. A normalization factor \( K_n \) is used to cancel any affects of this assumption. It is derived by summation of the generated photons over a bandwidth \( \Delta \nu_m \), calculated by interpolation of the gain from resonant and anti-resonant frequencies. The signal gain for the frequency interval \( \Delta \nu_m \) around a center frequency \( \nu_j \) is given by

\[
G(\nu) = \frac{(1 - R_1)(1 - R_2)G_S}{\left(1 - \sqrt{R_1 R_2 G_S}\right)^2 + 4G_S \sqrt{R_1 R_2} \sin^2 \phi}
\]

(16)

where \( G_S \) is the single pass gain at frequency \( \nu \) and the single pass phase shift \( \phi \) is
\[ \phi = \frac{2\pi\nu}{c} \int_0^L n_{eq}(z)dz \]  

Photon density generated within the frequency interval \( \Delta\nu_m \) centered at frequency \( \nu_j \) is given by

\[ N_{out} = \sigma_{in} \int_{\nu_j - \frac{\Delta\nu_m}{2}}^{\nu_j + \frac{\Delta\nu_m}{2}} G(\nu) d\nu \]  

If the photon density generation rate is calculated from the gain at resonant frequencies is compared with that of the equation (18), then the normalization factor \( K_j \) can be obtained from

\[ N_{Res_{out}} = \sigma_{in} \Delta\nu_m G(\nu_j) K_j \]  

\[ \Rightarrow K_j = \frac{\int_0^\phi G(\phi)d\phi}{\pi G(\nu_j)} = \frac{1}{\pi \sqrt{1 + \gamma^2}}, \quad \gamma = \frac{4\sqrt{R_1R_2}G(\nu_j)}{\left(1 - \sqrt{R_1R_2}G(\nu_j)\right)^2} \]  

3.2.4 Modelling of Carrier density generation rate

Optical amplification requires injection of carriers into the active region. The bias current injects the carriers into the active region and carrier confinement within the active region is achieved by using a double hetero-structure for the quaternary waveguide, which creates a potential well in the active waveguide region. It is further enhanced by proton (H\(^+\)) implantation of the InP layers adjacent to the InGaAsP active waveguide and also by using low dielectric material adjacent to the InP layers which serves the purpose of reducing the capacitance of the diode structure. For the integrated amplifier-modulator there exist three different sections, each having different bias or injection currents and therefore three different carrier densities in each of the regions for
amplification, isolation and modulation. The carrier density at a particular point \( z \) is
governed by the rate equations and is given by

\[
\frac{dn(z)}{dt} = I_n(z) - R(n(z)) \\
- \frac{\Gamma}{dW} \left( \sum_{k=1}^{N_k} g_n(v_k, n(z)) \left( N_{sk}^+(z) + N_{sk}^-(z) \right) \right) \\
- \frac{2\Gamma}{dW} \left( \sum_{j=0}^{N_j} g_n(v_j, n(z)) \left( N_j^+(z) + N_j^-(z) \right) \right)
\]  

(21)

### 3.2.5 Numerical Model

To solve the equations numerically the amplifier is segmented in 1-dimension
into a number of sections along the direction of propagation of the wave’s i.e, the \( z \)-axis.
All the material dependent quantities are calculated at the nodes which are located at the
section interfaces. Signal and Noise photon density rates are obtained by averaging the
positive and negative traveling signals and noise photon rates. Figure 3-4 shows
algorithm to determine the steady state values of the integrated amplifier modulator.[2]
Initially the numerical variables such as number of sections $N_z$, wavelength spacing for the noise calculation $K_m$ are initialized. Input conditions to amplifier-modulator are defined at $t=0$ including input signal wavelength, power, bias current to the amplifier and modulator, initial estimate of carrier density and various parameters. The amplifier is divided into three logical sections for amplification, isolation and modulation. The bias current in each section gives the corresponding injection carrier density in each logical section. The traveling wave coefficients of the forward and reverse waves are calculated
by cumulative numerical integration at each point $z$. These values are substituted in the rate equations and the rate of change of carrier density ($Q$) is calculated. Depending on the sign of $Q$ the carrier density estimate is updated by an appropriate factor. The entire process is solved by iteration until the values of the traveling coefficients settle to within a tolerance level in successive iterations.

The choice of the time step is critical and needs to be much smaller than the fastest transients that the electrical carriers or the optical signals can follow. A very small time step $\Delta t$ leads to a large simulation time and this gets especially severe when the model is used to simulate optical network where 100’s bits are required to simulate eye diagrams.
& the bit error rates of the system. The simulation time for the network simulation with this device level model easily runs into days. Hence a judicious choice for the time step, without sacrificing the accuracy is vital for being able to complete the simulations. The electrical carrier life time inside the optical waveguide

Dynamic Numerical Algorithm for amplifier-modulator [5]

Figure 3-6: Dynamic numerical algorithm for the amplifier

depends on the diode bias. If the optical PIN waveguide is deeply biased into the forward region, then the electrical carrier lifetime is determined by the drift current and
is similar to the current modulation rise and fall times. If the PIN waveguide is biased at the edge of the forward bias the carrier lifetime is decided by the diffusion time constant which is much slower. Typically the semiconductor optical amplifier-modulator is expected to receive un-modulated optical input signals. Hence the input optical signals are assumed to be much slower than the electrical modulation inputs. The time step $\Delta t$ for the dynamic simulation is chosen to be about $1/50^{th}$ of the fastest electrical input.

### 3.3 Simulation Results

The static and dynamic numerical models of the amplifier and amplifier-modulator were developed in matlab. A semiconductor optical amplifier static model was then simulated using optical parameters for a particular case of a device from experimental results that were published by Deguet et al [1] & Connelly.[2] This step helps correlate the results with the experimental values. The simulated amplifier had an active waveguide of width 0.4 µm, a height of 0.4µm and an active length of 600 µm along with a taper of 100µm on both ends which reduce the width from 0.4 µm down to zero at the facets. Amplifier has input and output coupling losses of 3dB each. The physical parameters of the amplifier used in the simulation are summarized in the Table 3.1.

### Table 3.1: Parameters of the SOA device [1,2]

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<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Central active region length</td>
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<td>600µm</td>
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<tr>
<td>Tapered active region length</td>
<td>$L_t$</td>
<td>100µm</td>
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<td>Active region width</td>
<td>$W$</td>
<td>0.4µm</td>
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<tr>
<td>Property</td>
<td>Symbol</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>Active region thickness or height</td>
<td>$d$</td>
<td>0.4 $\mu$m</td>
</tr>
<tr>
<td>Optical confinement factor</td>
<td>$\Gamma$</td>
<td>0.45</td>
</tr>
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<td>InGaAsP refractive index</td>
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</tr>
<tr>
<td>InP refractive index</td>
<td>$n_2$</td>
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</tr>
<tr>
<td>Equivalent refractive index with no carriers</td>
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<tr>
<td>Input coupling loss</td>
<td>$\eta_{\text{in}}$</td>
<td>3dB</td>
</tr>
<tr>
<td>Output coupling loss</td>
<td>$\eta_{\text{out}}$</td>
<td>3dB</td>
</tr>
<tr>
<td>Input facet reflectivity</td>
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</tr>
<tr>
<td>Output facet reflectivity</td>
<td>$R_2$</td>
<td>5e-5</td>
</tr>
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<td>Carrier independent absorption loss coefficient</td>
<td>$K_0$</td>
<td>6200</td>
</tr>
<tr>
<td>Carrier dependent absorption loss coefficient</td>
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<td>Linear radiative recombination coefficient</td>
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<td>1e7s$^{-1}$</td>
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<td>Bimolecular radiative recombination coefficient</td>
<td>$B_{\text{rad}}$</td>
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</tr>
<tr>
<td>Linear nonradiative recombination coefficient</td>
<td>$A_{\text{nrad}}$</td>
<td>3.5e8s$^{-1}$</td>
</tr>
<tr>
<td>Auger recombination coefficient</td>
<td>$C_{\text{aug}}$</td>
<td>3e-41m$^6$s$^{-1}$</td>
</tr>
<tr>
<td>Band gap energy quadratic coefficient</td>
<td>$a$</td>
<td>1.35</td>
</tr>
<tr>
<td>Band gap energy quadratic coefficient</td>
<td>$b$</td>
<td>-0.775</td>
</tr>
<tr>
<td>Band gap energy quadratic coefficient</td>
<td>$c$</td>
<td>0.149</td>
</tr>
<tr>
<td>Band gap shrinkage coefficient</td>
<td>$K_g$</td>
<td>9e-11eVm</td>
</tr>
<tr>
<td>Effective mass of electron in the CB</td>
<td>$m_e$</td>
<td>4.1e-32Kg</td>
</tr>
<tr>
<td>Effective mass of light hole in the VB</td>
<td>$m_{lh}$</td>
<td>5.06e-32Kg</td>
</tr>
</tbody>
</table>
Effective mass of heavy hole in the VB  \( m_{hh} \)  \( 4.19 \times 10^{-31} \text{Kg} \)

Differential of active region refractive index with carrier density  \( \frac{dn}{dn} \)  \( -1.8 \times 10^{-26} \text{m}^{-3} \)

Differential of equivalent refractive index with carrier density  \( \frac{dn_{eq}}{dn} \)  \( -1.34 \times 10^{-23} \text{m}^{-3} \)

For the amplifier gain curve, the amplifier was biased at various currents and the steady state simulation was run to obtain gain at various bias points.

Figure 3-7: Gain vs bias current of the semiconductor optical amplifier
Figure 3-7 shows the gain of the amplifier including coupling losses as a function of current bias to the amplifier with an input wavelength of 1537.7nm and an input power of 2.75µW (-25.6 dBm). From the Figure 3-7 it is observed that the current bias increases, gain saturation occurs and the results overall show very good agreement with experimental values. There is a slight discrepancy of 1-2 dB in the gain, which can be attributed to inaccuracies in modeling coupling losses and physical parameters $A_{rad}$ and $B_{rad}$.

3.3.1 Gain spectrum of the amplifier

The energy band gap of the optical amplifier determines the longest wavelength that can be amplified. The simulation model includes the effect of carrier density on the gain.

Figure 3-8: Gain spectrum of the amplifier for different carrier densities.
Increased carrier density lowers the energy required for the transition of electrons from the conduction to the valence band. This results in a shift in the peak of the gain spectrum towards shorter wavelengths or higher frequencies. The band gap shrinkage due to injected carrier density is included in the model. As expected Figure 3-8 shows the increase in carrier density shifting its gain peak spectrum towards shorter wavelengths.

3.3.2 Noise Spectra

The optical noise in the SOA is the result of the spontaneous emission in the gain bandwidth of the amplifier. The amplified spontaneous noise is the major contributor towards a high noise of the device. The noise power output varies with the input optical signal power being amplified. As the input optical signal power is increased the noise output power decreases. This is the direct result of the optical photons competing for available states for optical amplification. The noise spectrum is expected to have a gain ripple because of the resonant and anti resonant frequencies which are caused by weak reflection coupling back into the SOA. The gain ripple is easily observed in the noise spectrum plotted in Figure 3-9. The ripple magnitude of 0.6 dB compares well with published results [2]. The linear approximation used for the waveguide coupling used in the tapered waveguide near the input & output facets overestimates the spontaneous noise. This approximation can be improved by modeling the wave guide in beam-prop and plugging in the models into the amplifier or the amplifier-modulator model.
3.3.3 Fiber to Fiber Gain

The SOA gain varies with respect to the input power of the optical signal. A lower input optical signal power gives a very high gain and as the input power is increased the gain saturation starts to occur and the effective gain reduces. Figure 3-10 plots the total output power that can be observed for various input signal power. The output power spread is much smaller than the input optical signal power indicating gain saturation.
3.3.4 Carrier density profile

Carrier density varies along the length of the amplifier and a peak is indicative of the onset of the gain saturation. At low input signal powers or in the absence of any signal, the carrier density profile should have a spatial symmetry across the length of the amplifier since the SOA is symmetric and the back-propagating wave is negligible.

As the input signal power is increased from very low input power to very high input powers, the input signal starts to dominate the stimulated emission and the peak of the carrier density moves towards the input side of the optical signal. The plot in Figure 3-11 shows a shifting of the carrier density peak towards the right for higher input optical
powers. This plot helps in obtaining quick estimates of useful input optical power range for the SOA.

![Carrier density profile variation with input power](image)

**Figure 3-11: Carrier density profile variation with input power**

### 3.4 Integrated SOAM modeling

The Semiconductor optical amplifier-modulator can be built with ratios of the lengths of the amplification region to that of the modulation region and the sequence of the amplification and modulation regions as well. With the static and the dynamic simulation models we can study different possible configurations and use the ones for the device configuration that can be useful in optical local access networks. A few simple criterions can be identified for determining whether the SOAM can be useful in
optical access networks. The device should be able to work across the whole C-band fiber optical window of 1530nm to 1570nm. The device should be able to function outside of plant temperatures without any wavelength drift in the transmission band. The SOAM should also provide fiber to fiber insertion gain for all input power ranging from -30dBm to 0dBm. The device should also exhibit fiber-to-fiber insertion gain of 20dB or more for lower input powers. When the optical signal is modulated the output signals should exhibit an extinction ratio of at least 10dB or more for all the input wavelengths and across all input powers.

Two different structures a symmetrical and a non-symmetrical one with the ratio of the amplification region length to that of the modulation region length of 1/3 were studied for their characteristics. The symmetrical SOAM had a modulator section of length 400µm, a gain region of 400µm, an isolation region of 50µm and tapered regions of 75µm on either end. There are two possible configurations for this device. In the first possible configuration the optical signal passes through the gain section first and then the modulator section. In the second configuration, the optical signal passes through the modulator section and then the gain section. The non-symmetrical device has a gain section of length 200µm and modulation section of length 600µm. Ideally it is preferable to have a small modulation section, so that the capacitance it presents to the electrical driving circuit can be kept small.

The gain of the SOAM across the C-band wavelength window and for various input powers was simulated. The initial gain was evaluated with the static model of the
amplifier. The rise time, fall time & extinction ratio were simulated from the dynamic model of the SOAM. The rise time was defined as time taken for the optical output signal power to rise from the off-state value to within 90% of the final on-state value or within 0.47db of final value. The fall time of the amplifier was defined as the time taken for the optical output signal power to fall from the on-state value to below 10% of the on-state value or below 10dB of the on-state value.

3.4.1 Integrated SOAM device configuration A

The Device configuration A is a symmetrical structure with amplifier & modulator regions of length 400um each and with the optical input entering the amplifier region first. The fiber to fiber gain & extinction ratios were simulated for various powers for wavelengths across the optical C-band wavelengths and plotted to test for usability of the device as an Integrated Semiconductor optical amplifier modulator for use in local access networks.
3.4.1.1 Characteristics of SOAM device A

![Graph of Fiber to Fiber gain & Extinction ratio](image)

Table 3.2: Extinction ratios for device "A" across the C-band for various input powers

<table>
<thead>
<tr>
<th>Power (µW)</th>
<th>1530nm</th>
<th>1540nm</th>
<th>1550nm</th>
<th>1560nm</th>
<th>1570nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.663</td>
<td>15.877</td>
<td>13.484</td>
<td>12.35</td>
<td>11.127</td>
</tr>
<tr>
<td>100</td>
<td>17.819</td>
<td>16.432</td>
<td>15.429</td>
<td>14.7</td>
<td>13.991</td>
</tr>
<tr>
<td>1000</td>
<td>17.7</td>
<td>16.366</td>
<td>15.282</td>
<td>14.792</td>
<td>14.219</td>
</tr>
</tbody>
</table>
3.4.1.2 Rise & Fall times across the corners of wavelengths & powers

The rise time and fall time of the optical inputs after modulation were also simulated. The reference values and the 10% & 90% points were used to determine the rise and fall time. They are plotted across the four corners of usability of the device:

- Low input power & Short wavelength
- High input power & Long wavelength
- Low input power & Long wavelength
- High input power & Short wavelength

Figure 3-13: Rise and Fall times for Device A @1530nm and -30dBm input power
Figure 3-14: Rise and Fall times for device A at 1530nm and 0dBm input power
Figure 3-15: Rise and Fall time for Device A @1570nm and -30dBm input power
3.4.2 Integrated SOAM Device configuration B

Device configuration B is a symmetrical structure with amplifier & modulator regions of length 400um each and identical in structure to the device configuration A except that the optical input enters the modulator region first and subsequently passes through the amplifier region. The fiber to fiber gain & extinction ratios are simulated for various powers for wavelengths across the optical C-band wavelengths similar to the device A. plotted to test for the usability of the device as an Integrated Semiconductor optical amplifier modulator for use in local access networks.

Figure 3-16: Rise and Fall times for Device A @1570nm and 0dBm input power
3.4.2.1 Characteristics of SOAM device B

![Integrated Semi-conductor optical amplifier and modulator](image)

**Figure 3-17: Device configuration B characteristics**

- **Table 3.3: Extinction ratios for device "B" across the C-band for various input powers**
<table>
<thead>
<tr>
<th>Power</th>
<th>1530nm</th>
<th>1540nm</th>
<th>1550nm</th>
<th>1560nm</th>
<th>1570nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1µW</td>
<td>16.562</td>
<td>15.676</td>
<td>13.215</td>
<td>12.123</td>
<td>10.999</td>
</tr>
<tr>
<td>5µW</td>
<td>16.331</td>
<td>15.187</td>
<td>12.871</td>
<td>11.836</td>
<td>10.859</td>
</tr>
<tr>
<td>10µW</td>
<td>16.087</td>
<td>14.57</td>
<td>12.466</td>
<td>11.499</td>
<td>10.727</td>
</tr>
<tr>
<td>50µW</td>
<td>13.083</td>
<td>10.01</td>
<td>8.6141</td>
<td>8.6837</td>
<td>9.4483</td>
</tr>
<tr>
<td>100µW</td>
<td>9.9875</td>
<td>6.8669</td>
<td>5.5111</td>
<td>5.7618</td>
<td>7.4732</td>
</tr>
<tr>
<td>500µW</td>
<td>3.8957</td>
<td>2.0171</td>
<td>1.8787</td>
<td>1.9668</td>
<td>2.1</td>
</tr>
<tr>
<td>1000µW</td>
<td>2.3798</td>
<td>1.7189</td>
<td>1.7013</td>
<td>2.0392</td>
<td>2.1005</td>
</tr>
</tbody>
</table>

### 3.4.3 Integrated SOAM device configuration C

Device configuration C is a non-symmetrical structure with gain section of length 200um & modulator region of length 600um. The optical input enters the gain section first and subsequently passes through the modulator region. This device is also simulated for fiber-to-fiber gain & the extinction ratios across the wavelengths various power levels.

**Integrated Semi-conductor optical amplifier and modulator**
3.4.3.1 Characteristics of Device configuration C

Figure 3-18: Characteristics of Device configuration "C"

Table 3.4: Extinction ratios for device "B" across the C-band for various input powers

<table>
<thead>
<tr>
<th></th>
<th>1530</th>
<th>1540</th>
<th>1550</th>
<th>1560</th>
<th>1570</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>22.761</td>
<td>20.712</td>
<td>19.331</td>
<td>18.3</td>
<td>17.117</td>
</tr>
<tr>
<td>100</td>
<td>22.642</td>
<td>20.59</td>
<td>19.156</td>
<td>18.199</td>
<td>17.476</td>
</tr>
<tr>
<td>500</td>
<td>22.359</td>
<td>20.365</td>
<td>18.962</td>
<td>17.984</td>
<td>17.385</td>
</tr>
<tr>
<td>1000</td>
<td>22.299</td>
<td>20.307</td>
<td>18.903</td>
<td>17.929</td>
<td>17.334</td>
</tr>
</tbody>
</table>
3.4.4 SOAM Device Modeling Summary

Three device configurations have been modeled and evaluated for potential use in optical access networks. Device A exhibits good fiber-to-fiber gain and extinction ratios of 11-18dB across various wavelengths and power levels. Also as the input power increases the extinction ratio increases. This increase occurs because of gain saturation at higher optical input power levels. The net gain in the gain section reduces but the modulation regions has about the same loss at higher and lower input powers resulting in extinction ratio increasing with higher optical input power. Device B exhibits good gain across the wavelengths and power levels but has very low extinction ratios at higher input power levels. In device B, the optical signal is first modulated and then amplified. In this case gain saturation occurs at higher input powers when the signal is not modulated and normal gain can be expected in the gain section when the signal is modulated resulting in a low extinction ratio. Hence, the device B is considered unusable. Device C has similar characteristics as device A except that it has a smaller gain & higher extinction ratios. Since the speed of the modulation is proportional to length of the modulation section, device A will be used for simulations of optical access networks in the next chapter.
4. SOAM in Local Access Networks

Wavelength division multiplexing provides the ability to design high bit rate capacities in the local access optical systems. Wavelength division multiplexing in downstream direction can be easily implemented in local access optical networks. In the upstream direction, the several alternative technological choices such as spectral slicing, power combining & loop-back methods are still far away from converging on a single dominant solution. In this chapter we examine the use of an integrated SOAM for upstream transmission in local access network.

4.1 Local access optical network with SOAM

The OLT terminal in SOAM based local access networks generates both downstream wavelengths as well as the wavelengths for upstream transmission of data. The downstream wavelengths are modulated with data and then transmitted downstream over single mode fiber. The upstream un-modulated wavelengths are also generated in the OLT and transmitted downstream to the ONU.

![Figure 4-1: Loop back passive optical network](image)

A waveguide router is then used to route the upstream and downstream signals to several ONUs. They are routed such that one data modulated downstream wavelength
and one un-modulated wavelength are transmitted to each optical networking unit. The downstream and the upstream wavelengths are separated by optical filters in the ONU. The downstream wavelength is then received by the optical receiver while the un-modulated upstream wavelength is fed to the input of the SOAM. The SOAM then first amplifies the un-modulated wavelength and then modulates it with upstream data. This signal is then multiplexed and transmitted back to the router and then to the OLT either over the same fiber or a different fiber.

4.1.1 PON configurations with SOAM in the loop back

Three different approaches are possible in building SOAM based loopback WDM PON. Two of them would be one fiber solution and the other would be a two fiber solution. A fourth hybrid solution using both WDM & Power Splitting techniques in the PON is also possible.

4.1.1.1 Configuration A

In configuration A, the OLT uses a multi-wavelength source. The downstream wavelengths are modulated and sent downstream along with the un-modulated upstream...
wavelengths that also generated in the OLT. The OLT receives the upstream wavelengths that are modulated with upstream data by the SOAM in the ONU. These wavelengths traveling in the upstream direction on the same fiber are separated and then de-multiplexed. In the ONU, the received modulated downstream wavelengths and the un-modulated wavelengths are de-multiplexed. The un-modulated upstream wavelengths act as inputs to the SOAM and combined back into the optical fiber. The optical distribution network essentially consists of the waveguide router & the fiber.

This configuration has the advantage of the single fiber cost savings. Disadvantages include power penalties caused by nonlinear effects on the upstream signal because of the bi-directional transmission of the same wavelengths and near end & far end return loss and cross talk. The penalties are mitigated because of un-modulated wavelengths in one direction and also with power equalization that can be achieved in the upstream direction over the wavelength comb.

### 4.1.1.2 Configuration B

![Diagram of Configuration B](image-url)

Figure 4-3: SOAM based loop back passive optical access network over dual fiber
The OLT and the ONU in configuration B are identical except that the transmitted signals and the received signals are on different fibers. The optical distribution network in the downstream direction is identical to that of configuration A. In the upstream direction all the upstream signals from different ONUs are multiplexed and then transmitted to the OLT. A router can also be used to multiplex in the upstream direction but the passive optical multiplexers have low insertion losses compared to the router.

### 4.1.1.3 Configuration C

In a ring network the OLT & the ONU are identical to configuration A, but the distribution network is a ring type of network with several add-drop multiplexers. This type of design has the disadvantage of requiring the ability to tune the wavelengths independently because of presence of the add-drop multiplexers at several different locations outside the plant which leads to leading to different temperature conditions for each location. For this reason this is not a preferred approach.

### 4.2 Evaluation of SOAM based optical access networks

The SOAM based optical access network was evaluated for the following design parameters. For optical local access networks, ITU-T G.983.1[19] has several recommendations on the network requirements so that equipment can be standardized. SOAM based optical access network is evaluated by taking these recommendation into account. These require the network to be designed for a total range of 20Km including a differential logical range of 20Km and to meet any of the three classes of “outside the plant” loss budgets.

1. Class A: 5-20 dB loss
2. Class B: 10-25 dB loss
3. Class C: 15-30 dB loss

The current design was evaluated for a range of 20Km and a differential range of 20Km and for Class B outside the plant loss budget. Outside the plant loss budget does not include any losses that might be incurred in either the OLT or the ONU.

4.2.1 Loss Budget

ITU-T guidelines for class B losses of 10-25dB guidelines were defined for power splitting passive optical networks and are defined for a power splitting ratio of 1:16. The mean power loss of a 1x16 power splitter is 14dB. [21]. The power splitter in a Power splitting PON was replaced by a waveguide router in a WDM PON. The waveguide router has mean loss of 5.5dB at 1.5um. In the downstream direction the splice, splitter & connector losses in the OLT & ONU were 3.0dB. In the upstream direction, the upstream wavelengths would need to de-multiplexed before the optical receiver in the OLT. This adds about 5.5dB of OLT loss to the upstream signal. With cross talk and other miscellaneous penalties of 2.1dB, the net downstream direction loss budget is shown in Table 4.1

<table>
<thead>
<tr>
<th>Table 4.1: Downstream Loss Budget for SOAM based optical network</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITU-T class-B loss for PSPON</td>
</tr>
<tr>
<td>Power splitter loss</td>
</tr>
<tr>
<td>Wave Guide Router loss</td>
</tr>
<tr>
<td>Down stream OLT loss</td>
</tr>
<tr>
<td>Downstream ONU loss</td>
</tr>
<tr>
<td>Power penalties</td>
</tr>
</tbody>
</table>
With a receiver sensitivity of -35dBm and a transmitted power of 0dBm per wavelength the link margin would be an extremely healthy 10.5dB. The un-modulated upstream wavelengths transmitted by the OLT also undergo the same losses as the downstream wavelengths equaling to 22.5dB. Hence the worst case optical power received by the SOAM in the ONU would be -27.5dBm if we also take into account a 5dB transmitted power margin. Round trip outside the plant losses are 1.87 times the downstream losses [6]. Based on the downstream losses the upstream outside the plant network losses will amount to 15.3dB. The downstream router was replaced by a combiner. The ONU will also add an additional 1.5dB of macro-bend losses in the upstream direction for the loop back of the optical signal.

<table>
<thead>
<tr>
<th>Downstream outside the plant loss</th>
<th>17.4dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream outside the plant loss</td>
<td>15.4dB</td>
</tr>
<tr>
<td>Upstream ONU macro bend loss</td>
<td>1.5dB</td>
</tr>
<tr>
<td>Upstream OLT loss</td>
<td>5.5dB</td>
</tr>
<tr>
<td>Power penalties</td>
<td>2.1dB</td>
</tr>
<tr>
<td>Net loss + Penalties</td>
<td>24.5dB</td>
</tr>
</tbody>
</table>

The worst case input power received at the input of the SOAM located in the ONU is expected to be -27.5dBm from the calculations above. The SOAM fiber to fiber gain was
at least 21dB from the simulations across all the wavelengths in C-band. With a receiver sensitivity of -34dBm, this gives a very reasonable link margin of 3dB.

4.2.2 Dynamic margin

In Power splitting PONs, the upstream burst mode packets can undergo a variable path loss from 10dB to 25dB. The optical receivers in the OLT would need to support a minimum differential path loss of 15dB in addition to the dynamic margin to accommodate the power variations of the transmitters from different vendors resulting in a net guide line of 22dB. The differential loss in loop back based WDM PONs for upstream wavelengths includes the differential loss in the downstream direction too. The differential loss for the upstream wavelengths for a 0dBm input power was 9.5dB (22.5dBm -13dBm). The net differential loss for the upstream wavelengths at the OLT receiver would be 24.5dB. The gain saturation in the amplifier region of the SOAM reduces the differential path loss by at least 5dB(with input powers of 22.5dBm and 13dBm). If similar margin as in power splitting PON for variance or flexibility in transmitted equipment then the loop-back networks would need to handle a differential path loss of 26.5dB (24.5dB-5dB+7dB). The isolation cross talk from the adjacent channels at the de-multiplexers in the OLT results in a power penalty. This power penalty is given by the signal to interference noise ratio from the adjacent channels. It is given by the equation[22,23]

\[ \Delta P = 10 \log \left( 1 - \frac{1}{10^{0.1 \times SIR}} \right) \]

Where \( \Delta P \) is the power penalty incurred for a given signal to interference ratio (SIR). The power penalty is steep for SIR ratios of 5dB or less and is less than 1dB for a ratio of
7dB or more. In a 16 channel AWG with a typical adjacent channel isolation of 41dB, the cross talk in worst case is 29.2dB (41dB – 11.76dB) if all the channel powers are equal. For a differential path loss of 26.5dB, the SIR reduces to just 2.7dB. This requires either the network to be redesigned to reduce the differential path loss or the upstream transmitted powers to be equalized. This can be easily achieved in the amplifier portion of the SOAM. The gain current in the amplifier portion of the SOAM can be easily set to various values in different ONUs depending on the powers received at the input of the SOAM. This method can easily reduce the differential path loss by about 15dB by attenuating the higher received optical powers. If this method is used to reduce the dynamic margin then the 5dB of gain saturation in the SOAM cannot be used to reduce the differential path loss. The net SIR if variable attenuations/gains are set in the amplifier region of the SOAM would then be 29.2dB - 16.6dB, which would be a healthy 12.6dB. So the loop-back based optical network would require power equalization of upstream wavelengths to keep the cross talk penalties to less than 1dB.

4.2.3 Wavelength Separation at the ONU

In the loopback optical access network, the ONU receives two wavelengths from the OLT, the upstream and downstream wavelengths. These wavelengths are separated by at-least the free spectral range of the router. An optical filter is used to separate the wavelengths at the ONU. The separation of the wavelengths by atleast the free spectral range of the router which is greater than 16 times the channel spacing greatly eases the requirements of the optical filter. For a DWDM channel spacing of 50Ghz this translates to 800Ghz. This eliminates the necessity for the optical filter to be narrow band and the
center frequency to track the wavelengths variations even when a dense wavelength solution is used to expand the channel capacities.

4.2.4 Temperature variability

The AWG router in the optical distribution network uses narrow pass bands. Since this router is located outside the plant, the temperature dependence can cause the center frequencies of the pass bands to drift. These pass bands would also need to match those of the transmitter and the de-multiplexer/router at the OLT. Arrayed wave guide routers typically have a temperature dependence of about 0.01nm/°C. With the ITU-T guidelines for the outdoor operation range of -45 to 45°C, the wavelength drift would be 0.9nm or about 110GHz at 1550nm. Without a feedback mechanism to align the pass bands, the minimum channel spacing can only be 400GHz. This severely limits the number of wavelengths that can be used.

A simple mechanism is possible for this network to align the pass bands over the temperature that the outside the plant router has to operate and hence provide dense wavelength division multiplexing with channel spacing of 50GHz. A similar kind of router when used as a de-multiplexing device in the OLT and maintained at the same temperature as the outside the plant router will align the pass bands. This temperature can also be used to tune the transmitted wavelength comb. This method of reducing the temperature variation of pass bands is the simplest and only needs to done at the OLT.

4.2.5 Bandwidth

2.5GBps transmission can be achieved in both downstream and upstream directions. With one wavelength assigned to each ONU, it translates into 2.5GBps per ONU in either direction. If the typical value of 32 subscribers per ONU is used as per the ITU-T
guidelines, the bandwidth per subscriber translates into 78Mbps per subscriber in either direction. The downstream bandwidth can also be scaled to higher capacities by increasing the transmission rate and also adding more wavelengths.

4.3 Simulation of SOAM based loop-back WDM-PON

The optical network in configuration B was implemented in the photonic networking software(VPI transmission maker)[25]. The SOAM that is used in the ONU is implemented as a matlab co-simulation module in the VPI transmission maker. This model was used to determine the worst case bit-error rate & eye diagram. The photonic networking software helps model the optical networking equipment from the data sheet parameters.

![Figure 4-4: Schematic of SOAM based PON for optical network simulation](image)

The optical signals were represented in the time domain internally in the SOAM simulation model in the co-simulation module. The time step required for simulation of the model should be significantly less than the transient time or the fastest changing input rise time or fall time i.e. $\Delta t << \min(n_t \times L_{SOAM} / C_0, t_r)$. Also a multi-wavelength
amplification in the SOAM requires independent periodic time domain samples at different multiple wavelengths. The photonic simulation software allows many types of signal representations. A multi-wavelength source can be similarly represented to make it work with the co-simulation module. Representing each wavelength with an independent periodic sample band requires the channel spacing to be greater than the sample rate. For most WDM systems this would require different sampling rates a lower sampling rate in the network simulation and a much higher sampling rate for the SOAM co-simulation module. This was achieved by stepping up the sampling rate once entering the co-simulation module & again stepping down the sampling rate when exiting the SOAM simulation. The optical system was implemented in the photonic simulation software. Data sheet parameters from industrial products are used to model the optical networking equipment in the VPI transmission maker.

4.3.1 Channel Spectrum at the transmitter

Upstream wavelengths were allocated such that they are in the c-band to ensure optical amplification in SOAM. Also Downstream wavelengths were assigned such that upstream and downstream wavelengths were separated by an integral multiple of the free spectral range of the arrayed waveguide grating router. This ensured that each output port of the AWG was assigned one upstream & one downstream wavelength that are separated by at least one free spectral range of the router. For the simulated system the upstream wavelengths were allocated from 193.1THz to 196.1THz (16 wavelengths) and upstream wavelengths were assigned from 189.9THz to 192.9THz (16 wavelengths). Figure 4-5 shows the channel spectrum at the output of the transmitter in OLT.
4.3.2 Channel Spectrum at the input of the ONU

Both the upstream & downstream wavelength combs were transmitted and after the router the routed wavelengths were further transmitted over another fiber to the ONU. The channel spectrum included one upstream wavelength & one downstream wavelength. Figure 4-6 shows the simulated channel spectrum at the input of the ONU. The frequencies 189.9THz and 193.1THz represent the downstream and upstream wavelengths, respectively. The other wavelengths are the attenuated channels from the router passbands.
4.3.3 Bit Error Rate & Eye diagram

Figure 4-6: Channel Spectrum at the input of the Optical Networking Unit

Figure 4-7: Eye diagram of the upstream channel at the OLT
Optical system designs should typically meet the BER of $10^{-9}$. Simulation of such large numbers of bits is impractical and hence simulation models use statistical methods to estimate the noise components from short pseudo random sequences. Thermal noise dominates in networks without optical amplifiers. In systems with optical amplifiers, the amplified spontaneous emission (ASE) noise dominates. Since thermal noise is Gaussian, Gaussian techniques can be used to estimate BER for such systems. If the dominant noise is ASE, the signal-spontaneous beat noise & spontaneous-spontaneous beat noise fit the $\chi^2$ distribution and the $\chi^2$ statistics can be used to determine the BER. For the current configuration Gaussian method can be used for BER detection in the downstream direction, but the $\chi^2$ estimation should be used in the upstream direction as it will have ASE noise from the SOAM. Figure 4-8 shows the BER of the simulated system with the received optical power.

![BER vs. Received Power](chart.png)

*Figure 4-8: Bit Error Rate vs Received Optical Power of the upstream channel at the OLT*
Attenuators were used to model the miscellaneous power loss budgets and the link margins so that the simulated network represents the worst case BER rate.

4.4 Summary

A Loop back passive optical access network with integrated SOAM was simulated based on the ITU-T guidelines for optical access network. The results show that dense wavelength multiplexing is possible in local access networks without any laser transmitters at the customer premises. It was also shown that an acceptable BER can be achieved for the designed optical access network with ITU-T guidelines.
5. Conclusion

This work explored the use of traveling-wave semiconductor optical amplifier modulators as passive optical network elements at the remote end of an optical access network which employs a loop-back method for upstream communication. A physical-model of the traveling-wave semiconductor-amplifier-modulator was developed in matlab based on a numerical model of traveling-wave equations and a wideband gain model for the optical active region. Three different amplifier-modulator configurations were studied. One of them was identified for use in a Loop-back based passive optical network. A passive optical local access network was designed with the SOAM based on ITU-T guidelines. The design was evaluated and simulated to demonstrate the possibility of high capacity, wavelength division multiplexing passive optical networks in local access networks.
Bibliography


[14.] http://www.cablemodem.com


[19.] http://www.itu.int/rec/T-REC-G.983.1-199810-S


Appendix

Matlab program for the model.

```matlab
function [output] = SOAM_COSIM_FAST(input1, input2)

%clear all;
%close all;
global lchannel

format short g;
profile on -timer real;
input1

abs(input1.bands{1}.E);
start_t = clock;

for i=1:length(input2.band)
    figure;
    t=1:1:length(input1.bands{1}.E);
    plot(t*input2.dt*1e9,abs(input1.bands{1}.E));
    %ylim([10 110]);
end

%----------------------------------------------------------------------------------
%SOA geometrical and material properties
%Source: Semiconductor optical amplifiers by M. J. Connelly, page 71
%----------------------------------------------------------------------------------
y       = 0.892;
%Lc      = 600e-6;
%Lt      = 100e-6;
d       = 0.4e-6;
W       = 0.4e-6;
gama    = 0.45;
Kg      = 0.9e-10;
%Neq0    = 3.22; % (3.1825)
Neq0 = 3.1825;
dNeq_dn = -1.34e-26;
n1      = 3.22;
dn1_dn  = -1.8e-26;
n2      = 3.167;
Eta_in  = 3.0;
Eta_out = 3.0;
R1      = 5.0e-5;
R2      = 5.0e-5;
K0      = 6200;
K1      = 7500e-24;
A_rad   = 1.0e7;
B_rad   = 3.6e-16;
A_rad   = 3.6e8;
B_rad   = 0.0e-16;
Caug    = 3.0e-41;
Dleak   = 0e48;
a       = 1.35;
```

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\begin{verbatim}
b = -0.775;
c = 0.149;
Mec = 4.1e-32; % effective mass of electron in CB
Mhh = 4.19e-31;
Mlh = 5.06e-32;

%----------------------------------------------------------------------
% Fundamental Constants
%----------------------------------------------------------------------
C0 = 3e8;
h = 6.626e-34;
e = 1.602e-19;
Me = 9.109e-31;
Kb = 1.38e-23;
T = 300;

%----------------------------------------------------------------------
% Derived Variables
%----------------------------------------------------------------------
%L = Lc + 2*Lt;
Eg0 = e*(a + b*y + c*y^2);
r1 = R1^0.5;
r2 = R2^0.5;
Mhv = (Mlh^(3/2)+Mhh^(3/2))^(2/3); %effective mass of hole in VB
Nc = 2*(2*pi*Kb*T*Mec/h^2)^(3/2);
Nv = 2*(2*pi*Kb*T*Mhv/h^2)^(3/2);

%eta_in = log10(Eta_in/10);
%eta_out = log10(Eta_out/10);

%----------------------------------------------------------------------
% Numerical Variables
%----------------------------------------------------------------------

Km = 10; %Spontaneous emission averaging factor
Lt = 75e-6;
Lc = 400e-6;
Li = 50e-6;
Lm = 400e-6;

L = Lt + Lc + Li + Lm + Lt;
Nz = 100;
delta_z = L/Nz;
\end{verbatim}
\[ I_c = 100\times 10^{-3} \times \frac{2 \times L_c + L_t}{L_c + L_m + L_t}; \]
\[ I_m = 100\times 10^{-3} \times \frac{2 \times L_m + L_t}{L_c + L_m + L_t}; \]
\[ I_mH = I_m; \]
\[ I_mL = I_mH/6; \]
\[ \lambda_k = 1537.7 \times 10^{-9}; \] % Input wavelengths
\[ \text{Pin}_k = 2.75 \times 10^{-6}; \] % Input power - 25.6dbm

\[ \lambda_k1 = 10^{-9} \times [1530 1535 1540 1545 1550 1555 1560 1565 1570]; \]
\[ \lambda_k1 = 10^{-9} \times [1530 1570]; \]
\[ PV = [2.75 \times 10^{-6}]; \]
\[ PV = [10^{-7} 10^{-6} 10^{-5}]; \]
\[ PV = [10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-2}]; \]
\[ PV = [10^{-6} 5 \times 10^{-6} 10^{-5} 5 \times 10^{-5} 10^{-4} 5 \times 10^{-4} 10^{-3}]; \]

% \[ \delta_t = 10^{-12}; \]
\[ \delta_t = \text{input1.dt}; \]
\[ \frac{1}{t_r_I} = 50 \times 10^{-12}; \% 50ps; \]

\[ z_1 = (0: \delta_z: \delta_z \times \text{floor}(L_t/\delta_z)); \]
\[ z_2 = (\delta_z \times \text{floor}(L_t/\delta_z) + \delta_z: \delta_z: \delta_z \times \text{floor}((L_t+L_c)/\delta_z)); \]
\[ z_3 = (\delta_z \times \text{floor}((L_t+L_c)/\delta_z) + \delta_z: \delta_z: \delta_z \times \text{floor}((L_t+L_c+L_i)/\delta_z)); \]
\[ z_4 = (\delta_z \times \text{floor}((L_t+L_c+L_i)/\delta_z) + \delta_z: \delta_z: \delta_z \times \text{floor}((L_t+L_c+L_i+L_m)/\delta_z)); \]
\[ z_5 = (\delta_z \times \text{floor}((L_t+L_c+L_i+L_m)/\delta_z) + \delta_z: \delta_z: \delta_z); \]
\[ z = [z_1 z_2 z_3 z_4 z_5]; \]

\[ n_{Iz1} = \text{repmat}(I_c/(e \times d \times \bar{W} \times (L_c+L_t/2)),1,\text{length}(z_1)); \]
\[ n_{Iz2} = \text{repmat}(I_c/(e \times d \times \bar{W} \times (L_c+L_t/2)),1,\text{length}(z_2)); \]
\[ n_{Iz4} = \text{repmat}(I_m/(e \times d \times \bar{W} \times (L_m+L_t/2)),1,\text{length}(z_4)); \]
\[ n_{Iz5} = \text{repmat}(I_m/(e \times d \times \bar{W} \times (L_m+L_t/2)),1,\text{length}(z_5)); \]

\[ % \text{I}_{n} = [n_{Iz1} n_{Iz2} n_{Iz3} n_{Iz4}]'; \]
\[ % \text{I}_{n} = [z_1 \times I_c z_2 \times I_c z_3 \times I_c z_4 \times I_c]'; \]
% BEGIN Dynamic Current
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

$I_1 = I_mH;
$I_2 = I_mL;
$\%c0 = 2e-10/\delta_t;
$\%cr = 4e-10/\delta_t;
$\%cf = 8e-10/\delta_t;
$t_c0(1:lc0)=1;
$t_cr(1:lcr) = 1;
$t_cf(1:lcf) = 1;

$I_r = I_2 + (I_1-I_2)*(0:\delta_t:t_r_I)/t_r_I;
$I_f = flipr(I_r);

%IV_r = [ I1*t_c0  I_f  I2*t_cf  I_r  I1*t_cr];
%IV_f = [ I2*t_c0  I_r  I1*t_cr  I_f  I2*t_cf];
%IV = IVr;

IV=input2.band.E;
IVc = repmat(Ic,1,length(IV));
IVm = IV;
IVcn = IVc/(e*d*W*(Lc+Lt/2));
IVmn = IVm/(e*d*W*(Lm+Lt/2));

ivn = (IVcn + IVmn);
n_Iv3_100 = [(IVcn/10)'  (IVcn/100)'  (ivn/1000)'  (IVmn/100)'
            (IVmn/10)']';
%n_Iv3_200 = [(IVcn/1)'  (IVcn/4)'  (IVcn/16)'  (IVcn/64)'
            (IVcn/256)'  (ivn/1024)'  (IVmn/256)'  (IVmn/64)'
            (IVmn/16)']';
%n_Iv3_400 = [(IVcn/1)'  (IVcn/2)'  (IVcn/4)'  (IVcn/8)'  (IVcn/16)'
            (IVcn/32)'  (IVcn/64)'  (IVcn/128)'  (IVcn/256)'  (IVcn/512)'
            (ivn/1024)'  (IVmn/512)'  (IVmn/256)'  (IVmn/128)'  (IVmn/64)'
            (IVmn/32)''  (IVmn/16)''  (IVmn/8)''  (IVmn/4)''  (IVmn/2)'']';

n_Iv3 = n_Iv3_100;

$n_Iv1 = repmat(IVc/(e*d*W*(Lc+Lt/2)),length(z1),1);
$n_Iv2 = repmat(IVc/(e*d*W*(Lc+Lt/2)),length(z2),1);
$n_Iv4 = repmat(IVm/(e*d*W*(Lm+Lt/2)),length(z4),1);
$n_Iv5 = repmat(IVm/(e*d*W*(Lm+Lt/2)),length(z4),1);

IVn = [n_Iv1' n_Iv2' n_Iv3' n_Iv4' n_Iv5']';

I_n = IVn(:,1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% END Dynamic Current
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
\begin{verbatim}

i       = (1:1:Nz+1);
% delta_t = 1e-11;
% delta_z = L/Nz;
% z       = (i-1)*delta_z;
% Lm = 0;
% I_n = 130e-3;

% Physical Conditions

l1 = floor(Lt/delta_z) +1;
l2 = floor((Lt+Lc+Li+Lm)/delta_z) + 1;
taper(1:l1,:) = z(1:l1)'/Lt;
taper(l1+1:l2,:) = 1;
taper(l2+1:Nz+1,:) = (L - z(l2+1:Nz+1)')/Lt;
Gamma = gama*taper;
taper1 = taper;
taper1(1,:) = taper1(2,:);
taper1(Nz+1,:) = taper1(Nz,:);

%nu_k     = C0./lambda_k;
lambda_gb = 400e-9;                                 %Gain bandwidth in
wavelength 100nm                                    
nu_gb     = lambda_gb*C0/(1.550e-6)^2;              %Gain bandwidth in
frequency ~5e13                                      
nu_gb     = 4e13;

% Initial conditions for Carrier density, signal fields and spontaneous
% emissions

%for r = 1:length(lambda_k1)
%lambda_k = lambda_k1(r);
lambda_k = lambda_k1;
nu_k     = C0./lambda_k;
k       = (1:1:length(lambda_k));
Nk      = length(k);
nu_k    = repmat(nu_k,Nz+1,1); %list of all signal frequencies
across all sliced sections i (Nz)

nu_c0   = Eg0/h;
delta_nu_m = C0/(2*Neq0*(L));
\end{verbatim}
nu_c = round(nu_c0/delta_nu_m + 0.49999999)*delta_nu_m;
Nm = floor(nu_gb/(delta_nu_m*Km));
nu_j = (nu_c*Km*delta_nu_m:nu_c+Nm*Km*delta_nu_m));
j = (1:1:length(nu_j));
Nj = length(j);
nu_j = repmat(nu_j,Nz+1,1); % list of spontaneous emission freq across all sliced sections i (Nz)
Nn_plus(i,j) = 0;
Nn_minus(i,j) = 0;
Nn_plus_out(j) = 0;

I = Ic;
% for power looping variable
% for l = 1:length(PV)  % small L is the variable
Pin_k = PV(l);
Pin_k = (abs(input1.bands{1}.E)).^2;
Es_k_plus(i,(1:1:Nk)) = 0;
Es_k_minus(i,(1:1:Nk)) = 0;
Es_k_plus(1,:) = (0.5*Pin_k(1)./(h*nu_k(1,:))).^(1/2);

n0 = 1.5e24; % Initial Carrier density estimate
n(i,:) = n0;
w(i,:) = 0.1;
Q_ini = I/(e*d*L*W); % Initial estimate
Q_p(i,:) = Q_ini;
Q_d = Q_ini;
Q_tol = Q_ini/10;

aaa=0;
while any( abs(Q_d) > Q_tol)
    aaa= aaa+1;
    if ( mod(aaa,1000) == 0)
        aaa
    end
    if ( mod(aaa,500) == 0)
        Pin_k
        lambda_k*1e9
    end
    delta = n/Nc;
    epsilon = n/Nv;
    Egn = Eg0 - e*Kg*n.^(1/3);
    Efc = (log(delta) + delta.*(64 + 0.05524*delta.*(64 +
    delta.^((1/2))))*(-1/4))*Kb*T;
    Efv = -(log(epsilon) + epsilon.*(64 + 0.05524*epsilon.*(64 +
    epsilon.^((1/2))))*(-1/4))*Kb*T;
    Ea_j = (h*nu_j - repmat(Egn,1,length(j)))*Mhh/(Mec+Mhh);
    Eb_j = -(h*nu_j - repmat(Egn,1,length(j)))*Mec/(Mec+Mhh);
    Ea_k = (h*nu_k - repmat(Egn,1,length(k)))*Mhh/(Mec+Mhh);
\[Eb_k = -(h \cdot nu_k - \text{repmat}(Egn,1,length(k))) \cdot Mec \div (Mec + Mhh)\);

\[Fc_{nu_j} = 1 \div (1 + \exp((Ea_j \cdot \text{repmat}(Efc,1,length(j))) \div (Kb \cdot T)))\];
\[Fv_{nu_j} = 1 \div (1 + \exp((Eb_j \cdot \text{repmat}(Efv,1,length(j))) \div (Kb \cdot T)))\];
\[Fc_{nu_k} = 1 \div (1 + \exp((Ea_k \cdot \text{repmat}(Efc,1,length(k))) \div (Kb \cdot T)))\];
\[Fv_{nu_k} = 1 \div (1 + \exp((Eb_k \cdot \text{repmat}(Efv,1,length(k))) \div (Kb \cdot T)))\];

\[Rrad = Arad \cdot n + Brad \cdot n^2\];
\[Rnrad = Anrad \cdot n + Bnrad \cdot n^2 + Caug \cdot n^3 + Dleak \cdot n^{5.5}\];
\[R_n = Rrad + Rnrad\];
\[tau = n \div Rrad\];
\[Neq = Neq0 + dNeq_{dn} \cdot n\];
\[beta_k = \text{complex}(0, (2 \cdot \pi \cdot C0) \cdot 2 \cdot \text{trapz}(z, Neq) \cdot nu_k(1,:))\];
\[alpha = K0 + K1 \cdot \Gamma \cdot n\];
\[g_{m const} = (C0^2 \div (4 \cdot 2^{(1/2)} \cdot \pi^{(3/2)})) \cdot (4 \cdot pi \cdot Mec \cdot Mhh \div (h \cdot (Mec + Mhh)))^{(3/2)}\];
\[g_{m nu_j} = \text{gm const} \cdot 1 \div (\text{repmat}(tau \cdot (Neq^2),1,length(j)) \cdot (nu_j^2)) \cdot (Fc_{nu_j} \cdot \text{real}(nu_j - \text{repmat}(Egn,1,length(j)) \div h)^{(1/2)})\];
\[g_{m nu_k} = \text{gm const} \cdot 1 \div (\text{repmat}(tau \cdot (Neq^2),1,length(k)) \cdot (nu_k^2)) \cdot (Fc_{nu_k} \cdot \text{real}(nu_k - \text{repmat}(Egn,1,length(k)) \div h)^{(1/2)})\];
\[g_{m_{nu_j}} = \text{gm const} \cdot 1 \div (\text{repmat}(tau \cdot (Neq^2),1,length(j)) \cdot (nu_j^2)) \cdot (Fc_{nu_j} \cdot (1 - Fv_{nu_j}) \cdot \text{real}(nu_j - \text{repmat}(Egn,1,length(j)) \div h)^{(1/2)})\];

\[\text{gain net}_j = \text{repmat}(\Gamma,1,length(j)) \cdot \text{gm nu j n} - \text{repmat}(alpha,1,length(j))\];
\[\text{gain net}_k = \text{repmat}(\Gamma,1,length(k)) \cdot \text{gm nu k n} - \text{repmat}(alpha,1,length(k))\];

\[Es_k_{plus}(1,:) = (1-r1) \cdot (0.5 \cdot \text{Pin}_k(1) \div (h \cdot nu_k(1,:)))^{(1/2)} - r1 \cdot Es_k_{minus}(1,:) \cdot \text{exp}(beta_k)\];
\[Es_k_{plus} = \text{exp}(\text{cumtrapz}(z, \text{gain net k/2}) \cdot \text{repmat}(Es_k_{plus}(1,:),Nz+1,1))\];
\[Es_k_{minus}(Nz+1,:) = - r2 \cdot Es_k_{plus}(Nz+1,:)\];
\[Es_k_{minus} = \text{flipud}(\text{exp}(\text{cumtrapz}(z, \text{flipud(gain net k/2})) \cdot \text{repmat}(Es_k_{minus}(Nz+1,:),Nz+1,1))\];
\[Ns_k_{plus} = \text{abs}(Es_k_{plus})^{(2)}\];
\[Ns_k_{minus} = \text{abs}(Es_k_{minus})^{(2)}\];

\[Rsp_{nu_j} = \text{Km} \cdot \text{delta nu m} \cdot \text{repmat}(\Gamma,1,length(j)) \cdot \text{gl m nu j n}\];
\[Nn_{plus}(1,:) = R1 \cdot Nn_{minus}(1,:)\];
\[Nn_{plus} = \text{exp}(\text{cumtrapz}(z, \text{gain net j}) \cdot \text{repmat}(Nn_{plus}(1,:),Nz+1,1) + \text{cumtrapz}(-1, \text{Rsp_{nu_j}} \cdot \text{exp}(\text{cumtrapz}(z, -\text{gain net j})))\];
\[Nn_{minus}(Nz+1,:) = R2 \cdot Nn_{plus}(Nz+1,:)\];
\[Nn_{minus} = \text{flipud}(\text{exp}(\text{cumtrapz}(z, \text{flipud(gain net j))}) \cdot (\text{repmat}(Nn_{minus}(Nz+1,:),Nz+1,1) + \text{cumtrapz}(z, \text{flipud(Rsp_{nu_j})} \cdot \text{exp}(\text{cumtrapz}(z, \text{flipud(-gain net j)))))))\];
\[ Q_n = I_n - R_n - gama \cdot \text{taper} / (d \cdot W) \cdot \text{sum}((gm_{nu \_k_n} \cdot (N_{s_{k_{plus}} + N_{s_{k_{minus}}})/2)) + 2 \cdot \text{sum}((gm_{nu \_j_n} \cdot (N_{n_{plus}} + N_{n_{minus}})/2)); \]

\[ \text{Sign}_{\_ch} = \text{abs}((\text{sign}(Q_n) - \text{sign}(Q_p))/2; \]
\[ w = w \cdot (1 - \text{Sign}_{\_ch}/2); \]
\[ n = n \cdot \text{exp}(\log(1 + w) \cdot \text{sign}(Q_n)); \]
\[ \text{if} \quad (((\text{aaa} > 100) \&\& (\text{aaa} < 400)) || (\text{aaa} > 1000)) \]
\[ n = n + Q_n \cdot \text{delta}_{\_t}; \]
\[ \text{end} \]

\[ \% Q_d = Q_p - Q_n; \]
\[ Q_d = Q_n; \]
\[ Q_p = Q_n; \]
\[ \text{end} \]

\[ N_{s_{k_{out}}} = N_{s_{k_{plus}}}(Nz+1,:); \]
\[ N_{s_{k_{stat}}} = N_{s_{k_{plus}}}; \]

\[ t_{\_tr} = L \cdot \text{Eq0}/C_0; \]
\[ \% = 1/(\text{Brad} \cdot \text{sum}(n)/(Nz+1)); \]
\[ taul = 1/(\text{Brad} \cdot n); \]
\[ \% \text{Pre allocating for speed} \]
\[ m=(\text{length}(\text{IV}) - 1); \]
\[ N_{s_{out\_dyn}} = \text{zeros}(1,m); \]
\[ Q_n = 0; \]
\[ \text{length}(\text{IV}) \]
\[ \text{for} \quad m = 1:(\text{length}(\text{IV}) - 1) \]
\[ \delta = n/N_c; \]
\[ epsilon = n/N_v; \]
\[ Egn = E_{g0} - e \cdot K_{g\_n} \cdot (1/3); \]
\[ Efc = (\log(delta) + delta \cdot (64 + 0.05524 \cdot delta \cdot (64 + delta \cdot (1/2))) \cdot (1/4) \cdot K_b \cdot T; \]
\[ Ef_v = -(\log(epsilon) + epsilon \cdot (64 + 0.05524 \cdot epsilon \cdot (64 + epsilon \cdot (1/2))) \cdot (1/4) \cdot K_b \cdot T; \]
\[ E_{a\_j} = (h \cdot \text{nu}_j - \text{repmat}(Egn,1,length(j))) \cdot M_{hh} / (M_{ec} + M_{hh}); \]
\[ E_{b\_j} = -(h \cdot \text{nu}_j - \text{repmat}(Egn,1,length(j))) \cdot M_{ec} / (M_{ec} + M_{hh}); \]
\[ E_{a\_k} = (h \cdot \text{nu}_k - \text{repmat}(Egn,1,length(k))) \cdot M_{hh} / (M_{ec} + M_{hh}); \]
\[ E_{b\_k} = -(h \cdot \text{nu}_k - \text{repmat}(Egn,1,length(k))) \cdot M_{ec} / (M_{ec} + M_{hh}); \]
\[ Fc_{\_nu\_j} = 1/(1 + \exp((E_{a\_j} - \text{repmat}(Efc,1,length(j))) / (K_b \cdot T))); \]
\[ Fv_{\_nu\_j} = 1/(1 + \exp((E_{b\_j} - \text{repmat}(Ef_v,1,length(j))) / (K_b \cdot T))); \]
\[ Fc_{\_nu\_k} = 1/(1 + \exp((E_{a\_k} - \text{repmat}(Efc,1,length(k))) / (K_b \cdot T))); \]
\[ Fv_{\_nu\_k} = 1/(1 + \exp((E_{b\_k} - \text{repmat}(Ef_v,1,length(k))) / (K_b \cdot T))); \]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%
\[ % Arad = 0; \]

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Rrad = Arad*n + Brad*n.^2;
Rnrad = Anrad*n + Bnrad*n.^2 + Caug*n.^3 + Dleak*n.^5.5;
R_n = Rrad + Rnrad;
tau = n./Rrad;

% tau = 1.5e-9;

Neq = Neq0 + dNeq_dn*n;
beta_k = complex(0,(2*pi/C0)*2*trapz(z,Neq)*nu_k(1,:));
alpha = K0 + K1*Gamma.*n;

Rsp_nu_j = Km*delta_nu_m*repmat(Gamma,1,length(j)).*gl_m_nu_j_n;
Nn_plus (1,:) = R1*Nn_minus (1,:);
Nn_plus = exp(cumtrapz(z,gain_net_j)).*(repmat(Nn_plus (1,:),Nz+1,1) + cumtrapz(z,Rsp_nu_j.*exp(cumtrapz(z,-gain_net_j))));
Nn_minus (Nz+1,:) = R2*Nn_plus (Nz+1,:);
Nn_minus = flipud(exp(cumtrapz(z,flipud(gain_net_j)))).*(repmat(Nn_minus (Nz+1,:),Nz+1,1) + cumtrapz(z,flipud(Rsp_nu_j).*exp(cumtrapz(z,flipud(-gain_net_j))))));
\[ Q_n = Ivn(:,m+1) - R_n - gama.*taper/(d*W).*(sum((gm_nu_k_n.*(Ns_k_plus + Ns_k_minus)),2) + 2*sum((gm_nu_j_n.*(Nn_plus + Nn_minus)),2)); \]

% \( Ns_k_{\text{dyn}}(:,m) = Ns_k_{\text{plus}}; \)
% \( Nn_j_{\text{avg}}(:,m) = Nn_plus(Nz+1,:); \)
\( \text{delta}_n = Q_n*\delta_t; \)
\( n = n + \text{delta}_n; \)
\( \text{Nn}_\text{plus out} = \text{Nn}_\text{plus out} + \text{Nn}_\text{plus}(Nz+1,:); \)
end

\% \( \text{N}_\text{out} = 0.5*(1-R2)*[Ns_k_{\text{dyn}}(Nz+1,:), Ns_k_{\text{dyn}}(Nz+1,m)]; \)
\( \text{N}_\text{out} = 0.5*(1-R2)*[Ns_{\text{out dyn}}, Ns_{\text{out dyn}}(m)]; \)
\( E_{\text{out}} = (N_{\text{out}}*h*nu_k(1,1)).^(1/2); \)
\( P_{\text{out}} = (E_{\text{out}}).^2; \)
\( P_{\text{out dbm}} = 10*log10(P_{\text{out}}*1e3); \)

\( \text{Nu}_n_{\text{cf}} = (\text{nu}_c:Km*\delta_nu_m:(\text{nu}_c+Nm*Km*\delta_nu_m)) + Km*\delta_nu_m/2; \)
\( \text{Nu}_n_{\text{be}} = (\text{nu}_c:Km*\delta_nu_m:(\text{nu}_c+(Nm+1)*Km*\delta_nu_m)); \)
\% \( \text{Nn}_j_{\text{avg}} = 0; \)
\% \( \text{for} \ m=1:(\text{length}(IV)-1) \)
\% \( \text{\text{Nn}_j_{\text{avg}} = Nn_j_{\text{avg}} + Nn_plus(Nz+1,:);} \)
\% \( \text{end} \)
\( m=\text{length}(IV); \)
\( \text{Nn}_j_{\text{avg}} = \text{Nn}_\text{plus out}/m; \)
\( \text{Pn}_{\text{avg}} = 0.5*(1-R2)*\text{Nn}_j_{\text{avg}}.*(h*(\text{Nu}_n_{\text{cf}} - Km*\delta_nu_m/2)); \)
\( \text{Gain}_{\text{stat}} = 10*\log10(0.5*(1-R2)*\text{Ns}_{\text{k stat}}(Nz+1,1)*h*nu_k(1,1)/\text{Pin}_k(1)); \)
\( \text{Gmax} = \text{Gain}_{\text{stat}}; \)

%%%%%%%%%%%%%%%%%%%%%%%%%
\% Rise & fall time plots
%%%%%%%%%%%%%%%%%%%%%%%%%
figure;
hold;
[AX, HA(1), HA(2)] = plotyy(t*1e9,P_{\text{out dbm}},t*1e9,IVm*1e3);
% \( \text{hlines = plot(t*1e9,}\text{Gmax},t*1e9,\text{Gmax}-0.46,t*1e9,\text{Gmax-10}); \)
legend(HA,'Gain','Current',4);
hold;
title('Rise & Fall times','FontSize',14),
xlabel('Time (ns)','FontSize',14);

axes(AX(1));
set(gca,'ycolor','k');
ylabel('Fiber to Fiber gain (dB)','FontSize',14);
if (Gmax > 20)
\% \( \text{ylim([5 25])}; \)
end
axes(AX(2));
set(gca,'ycolor','k');
ylabel('Current (mA)','FontSize',14);
ylim([10 110]);
set(gca,'ytick',[10:50:110]);
% end %end of power looping
%end %end of wavelength looping

% Set the type of the signal
Sout.type = 'osignal';
% Set the time grid spacing
Sout.dt = input1.dt;
% Set the frequency grid spacing
Sout.df = input1.df;
% Set the time stamp
Sout.t0 = 0;
% Set the duration of the signal (=Duration/time grid spacing)
Sout.T = input1.T;
% Set the lowest frequency of the structure (grid points)
Sout.f0 = min(input1.f0, ceil(Nu_n_be(1)/Sout.df));
% Set the highest frequency of the structure (grid points)
Sout.f1 = max(input1.f1, ceil(Nu_n_be(length(Nu_n_be))/Sout.df));

% Create noise bins with equal spacing
Sout.noise = cell(1,length(Nu_n_cf));
for bin = 1 : length(Nu_n_cf)
    % Set the type of the noise bin
    Sout.noise{bin}.type = 'onoise';
    % Set the lower frequency of the noise bin
    Sout.noise{bin}.f0 = ceil(Nu_n_be(bin)/Sout.df);
    % Set the upper frequency of the noise bin
    Sout.noise{bin}.f1 = ceil(Nu_n_be(bin+1)/Sout.df);
    % Initialize the four element stokes vector of the noise bin
    Sout.noise{bin}.S = [Pn_avg(bin) 0 0 0];
end;

Sout.channels = cell(1,0);
% for ch = 1:1:1
%    y.channels{ch}.type = 'ochannel';
%    y.channels{ch}.f0 = [ ]; %input1.bands{1}.f0 + floor(2e12/y.df);
%    y.channels{ch}.f1 = [ ]; %input1.bands{1}.f1 + floor(2e12/y.df);
%    y.channels{ch}.S = [ ];
% % end;
%length(Sout.channels)

Sout.bands = cell(1,1);
for u = 1 : 1
    % Set the type of the signal
    Sout.bands{u}.type = 'oband';
    % Set lower frequency of sampled band
    Sout.bands{u}.f0 = input1.bands{1}.f0;
    % Set upper frequency of sampled band
    Sout.bands{u}.f1 = input1.bands{1}.f1;
    % Set polarization to x-polarization
    Sout.bands{u}.azi = 0;
    Sout.bands{u}.ell = 0;
    Sout.bands{u}.E = [ ];

    Sout.bands{u}.E = E_out;
% Create empty arrays corresponding to arbitrary polarization
Sout.bands{u}.Ex = [];  
Sout.bands{u}.Ey = [];  
Sout.bands{u}.labelset = cell(1,1);  
%Sout.bands{u}.labelset = input1.bands{u}.labelset;  
Sout.bands{u}.labelset{1}.type = 'label';  
Sout.bands{u}.labelset{1}.label = 'test9_vtmu.TxExtModLaser_vtmgl.LaserCW1';  
Sout.bands{u}.labelset{1}.seqno = 0;  
Sout.bands{u}.labelset{1}.info = '';  
end;
output = Sout;
end_t = clock;
run_t = etime(end_t, start_t)
profile off;
%profile viewer;