**All OPTICAL SIGNAL PROCESSING: APPLICATION OF NONLINEARITY IN SEMICONDUCTOR OPTICAL AMPLIFER**

**Dr Shikha Jaiswal,**

**Associate Professor, Department of Physics, Feroze Gandhi College, Raebareli.**

**shikhajk@gmail.com**

**Abstract**

**Optics has been used in signal processing for a number of years. Optical signal processing was a hot research area in 1980s. But this area could not get success due to materials limitations that prevented integrated optical chips. The optical signal processing is increasingly important in future ultra-high capacity telecommunication network. The development of all-optical logic technology is important for a wide range of applications in all-optical networks including high speed all-optical packet routing. An important step in the growth of this technology is a demonstration of optical logic elements and circuits that can also operate at higher speed up to Tbit/sec. The optical carrier frequency range 1013 to 1016 Hz provides enormous potential bandwidth with superior information carrying capacity over a long transmission distance. The need of higher capacity is continuing to encourage research in wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM) based transmission systems, which need optical demultiplexing and wavelength conversion technology. Therefore, for high-speed optical networks, it is required to develop the all-optical gates to avoid power consumption in opto-electronics conversion. All optical logic gates perform computing operations, storage and transmission of data using light also known as optical computing.. Optical technology promises massive upgrades in the efficiency and speed of computers, as well as significant shrinkage in their size and cost. All optical Signal processing i.e. wavelength conversion, logic functions, signal representation and retrieving in all optical domain may help to realize all kinds of situation in optical domain. The key to achieve all optical signak processing and particularly computing functions is to use a non-linear optical material where different light beams can interact. Out of the many non-linear materials investigated it is found the Semiconductor Optical Amplifier (SOA), a non-linear device that has emerged as most appropriate solution for all optical signal processing/computing. Semiconductor optical amplifier is very promising device for all optical processing/computing as it is compact, high gain, fast response, strong refractive index variation, easy to manufacture and integration, and power efficient.**

**Keywords: optical signal processing, opto-electronic conversion, all optical switching.**

1. **Introduction**

In the present scenario communication traffic is increasing day by day due to the increase in various services based on communication network. This may cause a serious problem of power consumption. A communication network basically has two functions: transmission and switching. Information bits are transmitted from origin to final destination through transmission channel such as optical fiber cable. During transmission there are many nodes in the path, at each node switching takes place so as to route the signal from the origin to the destination along a prescribed pathway. Switching in the optical domain can be broadly classified as optical circuit switching and packet switching. Optical circuit switching results in increased power consumption that increases as the number of wavelength increases. As the network is becoming more and more Internet Protocol (IP) based, optical circuit switching becomes more and more inefficient and hence use of Optical Packet switching was started. The important steps taking place in an optical packet switching are input alignment, buffering, wavelength conversion, signal conditioning required for making it compatible for switching the packet to the desired output port. Thus in order to realize optical packet switching, many advanced all-optical signal processing functions should be realized and combined such as all-optical header recognition, buffer, switching, wavelength conversion, logic functions, storage etc.

Optical computing is immune to electromagnetic interference and also free from electronic short circuit, because photons of different wavelengths can travel together in same fiber without any cross talk. Photons have low loss transmission and large band width offering several channel multiplexing. When we are talking about optical computing it implies all-optical systems, which means one optical signal in circuit, controlling another optical signal by switching it off and on without external electronic component. When it transmits light, it is considered ‘1’ and when it blocks light, it is considered ‘0’. Optical storage will provide extremely optimize way to store data with space requirement as compared to for lesser than today’s silicon machine. Short circuit is avoided in optical computing as light beam of different wavelength s can cross each other without interference. For optical computing, we use coherent source which is a major drawback as any imperfection or dust on optical component will create unwanted interference pattern. Thus, due to coherency and scattering effect, the accuracy in the results of optical computing may be degraded.

Nonlinearity is mainly due to harmonic motion of bound electrons under the influence of applied field. Non-linear materials are those, which interact with light and modulate its properties. Several of the functions in optical domain, require efficient nonlinear materials for their operations. Most of the available nonlinear materials required large amount of energy for responding or switching and hence their use in optical computing is restricted. Non-linear optical effects usually help in all optical computing. Optical computing technology is, in general, developing in two directions [1]. One direction is to build hybrid computers that have the same architecture as present day computers but using optics for certain functions like connections, switching etc. Another approach is to generate a completely new kind of computer that can perform all functions in optical domain. The real optical computers include optical logic gates, optical switches, optical interconnections and optical storage devices. In the hybrid optical/electronic computers, optical connections within electronic computer systems will speed up the data between the parts of a computer. Optical switches will mix in with electronic processors to move information quickly without generating much heat. Optical data storage devices will also be important in the development of optical computers. These storage devices include advanced optical CD-ROMs and Read/Write/Erase and other advanced optical memory technologies.

**II. Nonlinear Effects in Optical Fiber**: Silica glass shows lower nonlinearity as compared to other nonlinear materials. As SiO2 has inversion symmetry, second-order susceptibility does not contribute for nonlinear response. Only third-order susceptibility is responsible for nonlinear effects in Silica fiber and its value for silica glass is smaller than crystals and liquids [2]. Optical fiber based optical computing devices enjoy several advantages. Firstly, fiber based devices are easily coupled to the optical fiber transmission link, decreasing the coupling losses. Secondly, the nonlinear effects are very fast (on the time scale of tens of femtoseconds), enabling fast processing far beyond 1 Tb/s. Thirdly, due to the passive nature of the device, no noise is added to the signal in the processing. The Optical computing devices based on highly nonlinear fiber are attractive because of their high conversion bandwidth, low attenuation, larger Raman gain coefficient, shifting of zero dispersion wave length, compatibility with optical fiber system.. Nonlinear Effects in Optical Fiber can be classified into two as given in Table1.1 The first category includes the nonlinear inelastic scattering process. These are Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) effects. In fact these effects are used for amplification at certain other wavelengths. The second category of nonlinear effects arises from intensity– dependent variations in the refractive index in a silica fiber, which is known as the Kerr effect. These effects include Self Phase Modulation (SPM), Cross-Phase Modulation (XPM), Four-Wave Mixing (FWM). [3].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| S.N | Non-linearity | Single channel | Multi-channel | Dependence |
| 1 | Index | SPM | XPM,FWM | Intensity dependent variations in refractive index |
| 2 | Scattering | SBS | SRS | Optical power density dependent |

Table 1.1 Classification of non- linearity in optical fiber

In the case of scattering related nonlinear effect, disproportional attenuation occurs usually at high optical power levels. The nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes at different frequency. It depends on the optical power density and become significant above threshold power level. Most important types of nonlinear scattering within fibers are stimulated Brillouin and Raman scattering, both of which are only observed at high optical power densities in long single-mode fibers. These scattering mechanisms in fact gives optical gain but with a shift in frequency.

**Stimulated Brillouin scattering (SBS)**: Thermal molecular vibration within the fiber is mainly responsible for Stimulated Brillouin Scattering. In fact scattering modulates the light and thus scattered light appears as upper and lower sidebands which are separated from the incident light by the modulation frequency. The incident photon in this scattering process produces a phonon of acoustic frequency as well as a scattered photon. The frequency shift is maximum in backward direction, reducing to zero in forward direction making SBS mainly a backward process.

**Stimulated Raman Scattering (SRS)**: The incident photon in this scattering process produces a high frequency optical phonon rather than an acoustic phonon as in SBS. It occurs both in forward and backward directions in an optical fiber. The difference between Brillouin and Raman scattering is that the Brillouin generated phonons i.e. acoustic phonons are coherent and give rise to an acoustic wave in the fiber, while in Raman scattering the optical phonons are incoherent and no acoustic wave is generated.

**Self-phase modulation (SPM):** SPM is the major nonlinear effect in a single channel optical fiber system. Variation in signal intensity produces variation in refractive index in a medium and thus the refractive index varies with Intensity as given below in equation 1.1 [3].

$n=n\_{0}+n\_{2}I=n\_{0}+n\_{2}\frac{P}{A\_{eff}}$ 1.1

where *n0* is the original refractive index of the material and *n2*is the nonlinear index coefficient, *P* is the optical power and *Aeff* is the effective core area. The leading edge will experience a positive refractive index gradient *(dn/dt)* and trailing edge will experience a negative refractive index gradient *(−dn/dt)*. This variation in refractive index results in variation in phase, as shown in Fig 1.1.



Fig.1.1: Spectral broadening of a pulse due to self-phase modulation [3].

The variation in optical phase resembles with the variation in optical signal. This nonlinear phase modulation is self-induced thus known as self-phase modulation. The main parameter γ which indicates the magnitude of the nonlinear effect for SPM [3] is given by equation 1.2

$γ=\frac{2π}{λ}\frac{n\_{2}}{A\_{eff}}$ 1.2

where λ is free space wavelength. Different parts of the pulse undergo different phase shift because of intensity dependence refractive index change that results in phase fluctuations resulting in frequency chirping. The rising edge of the pulse shifts in upper side whereas the trailing edge experiences shift in lower side. Hence primary effect of SPM is to broaden the spectrum of the pulse, keeping the shape of the pulse unaltered. The SPM effects are more pronounced in systems with high-transmitted power because the chirping effect is proportional to transmitted signal power. The phase shift Δφ arising from SPM [3] is given by equation 1.3

$Δϕ=\frac{dφ}{dt}=γL\_{eff}\frac{dP}{dt}$ 1.3

Where Leff is the effective length of fiber assumed with constant power. To increase the repeater spacing, more power must be launched into each fiber. As soon as it crosses the threshold level, SPM effect is observed which results in pulse spreading. The use of large effective area fibers (LEAF) reduces intensity inside the fiber and hence SPM effect on the system.

**Cross phase modulation (XPM):** The intensity dependence of refractive index leads to another nonlinear phenomenon known as cross-phase modulation (XPM). When two or more optical pulses propagate simultaneously, the cross-phase modulation is always accompanied by SPM and occurs because the nonlinear refractive index seen by an optical beam depends not only on the intensity of that beam but also on the intensity of the other co- propagating beams. In fact XPM results in power fluctuations in a particular wavelength channel to phase fluctuations in other co-propagating channels resulting in asymmetric spectral broadening and distortion of the pulse shape due to XPM. It affects the system performance through the same mechanism as SPM i.e. chirping frequency and chromatic dispersion, but XPM can damage the system performance even more than SPM. XPM influences the system severely when number of channels is large. Theoretically, for a 100-channels system, XPM imposes a power limit of 0.1mW per channel [4]. Effect of XPM can be greatly minimized in WDM systems by operating over standard non-dispersion shifted single mode fiber. Like SPM, the XPM also depends on interaction length of fiber and cross sectional area. The long interaction length is always helpful in building up this effect up to a significant level and thus using for design of all-optical computing devices. Analogous to SPM, for two interacting wavelengths the XPM induced phase shift Δφ [3] is given by equation 1.3

$Δϕ=\frac{dφ}{dt}=2γL\_{eff}\frac{dP}{dt}$ 1.3

When multiple wavelengths propagate in a fiber the total phase shift will be sum of the phase shifts due to SPM and XPM effects for all the wavelengths.

**Four wave mixing (FWM)** FWM process results from third order nonlinear susceptibility (χ(3)) in fiber. If three optical fields with carrier frequencies ω1, ω2 and ω3, co-propagate inside the fibre simultaneously, nonlinear susceptibility (χ(3)) generates a fourth field with frequency ω4, which is related to the input frequencies by a relation, ω4 = ω1±ω2±ω3.

 In quantum-mechanical context, FWM occurs when photons from one or more waves are annihilated and new photons are created at different frequencies such that net energy and momentum are conserved during the interaction. SPM and XPM nonlinear phenomena affect high bit rate systems, but the FWM effect is independent of the bit rate and is critically dependent on the channel spacing and fiber dispersion. Decreasing the channel spacing increases the four-wave mixing effect. Similar is the effect of decreasing the dispersion. Four-wave mixing presents a severe problem in WDM systems using dispersion-shifted fibers (DSF). The effect of four wave mixing can be minimized by changing fiber dispersion and the channel spacing. The signal waves and generated waves have different group velocities and thus dispersion varies with wavelength. This destroys the phase matching of the interacting waves and lowers the efficiency at which power is transferred to newly generated frequencies. Due to chromatic dispersion, different waves travel with different group velocities. This results in reduction in efficiency of FWM. A dispersion-shifted fiber is used for this purpose. The FWM also imposes limitations on the maximum transmitted power per channel.

Raman and Brillouin gain coefficients in silica fibers are smaller in magnitude as compared with other nonlinear materials. Thus relatively long lengths of fibers are required to have significant nonlinear effects. Further the threshold power level for nonlinear effects in optical fibers is relatively low. The product of peak optical intensity and effective length of the medium is the figure of merit for judging the efficiency of a nonlinear process. The first highly nonlinear fiber (HNLF) with relatively low attenuation was developed by Nippon Telegraph and Telephone Corporation (NTT) in 1986. In 1997, Sumitomo Electric Industries, Ltd. demonstrated a dispersion-shifted HNLF with a zero-dispersion wavelength of 1.55 μm, and opened the door to today's nonlinear applications in all optical signal processing [5].The special category of fiber known as Photonic crystal fiber are used efficiently in ultra- fast optical signal processing [3].

 **The main limitation of optical fiber based optical computing devices is that larger length of fiber is required to produce a significant amount of nonlinear effect. Also the switching energy required for a particular switching operation in fiber based devices is high as compared to that of SOA based devices***.*

**III. Nonlinear organic materials**: Due to their high nonlinearities and flexibility of molecular design, organic materials have become popular among all optical computing devices. Few of these materials, which belong to the classes of phthalocyanines and polydiacetylenes have been used in the NASA/MSFC laboratories for designing all-optical logic gates and were also processed in space by the MSFC group and others [1]. These organic compounds are promising components for optical thin films and waveguides. Phthalocyanines are large ring-structured porophyrins for which large and ultrafast nonlinearities have been observed. These compounds exhibit strong electronic transitions in the visible range of frequencies and have high chemical and thermal stability up to 400oC. Third order susceptibility of phthalocyanine has been measured, which is a measure of its nonlinear efficiency and is million times larger than that of other nonlinear material. These materials are frequently used as a photosensitive organic material for photovoltaic, photoconductive, and photo electrochemical applications [1]. Polydiacetylenes are zigzag polymers having largest non resonant susceptibility. This nonlinear property can be used for switching in all-optical domain. And hence polydiacetylenes are among the most widely investigated class of polymers for nonlinear optical applications. Their sub picoseconds time response to laser signals makes them candidates for high-speed optoelectronics and information processing [1]. Growth of the films of this material on ordered organic and inorganic substrates under various processing conditions are useful for preparing highly oriented films. One such processing condition i.e. effect of microgravity on the structures and properties of thin films and crystals has been demonstrated by NASA Scientists. Group of NASA scientists observed intrinsic optical bistability and demonstrated an all-optical AND-logic gate in vapor-deposited thin films of metal free phthalocyanine. All-optical NAND Gate with picoseconds response had been developed by using properties of polydiacetylene [1].

**IV.Semiconductor Optical Amplifier** The Optical computing devices based on SOA are attractive because of their high gain, high saturation output power, wide gain bandwidth, compactness and integrability with other photonic devices. The limitation of use of SOA for optical computing devices is its polarization dependent characteristic which results in pattern effect. The basic structure of an SOA is the same as that of semiconductor laser diodes, except there is an anti-reflection (AR) coating on both facets. Sometimes the tapered structure of the waveguide close to the facets is used to minimize the reflection at both facets. The active layer, which can either be bulk, quantum well, or quantum dots, is sandwiched between the other semiconductor layers as a gain The basic structure of a semiconductor optical amplifier is given in Fig. 1.2 [6].

Material composition for the active layer which has a lower band gap, is such that when a forward voltage is applied to the junction, free electrons from the n-type material and holes from the p-type material travel towards the active layer. These charge carriers are trapped in this layer. A typical amplifier chip is ~0.6 to 2 mm long, divided into three parts i.e. p-cladding layer, n-cladding layer and a gain region. The schematic design of semiconductor optical amplifier chip is shown in Figure 2.

Population inversion is created by applying appropriate pumping. Thus, stimulated emission (SE) occurs due to the generation of photons with the same wavelength and phase as the incoming photons. On the other hand, the electrons lying in ground state absorb the energy of a passing photon and get excited. This gives rise to the process of stimulated absorption, opposite of stimulated emission.

When population inversion is sufficiently large, the stimulated emission will dominate the stimulated absorption and light amplification is achieved [6]. Gain of SOA, acting as an amplifier is expressed by the following equation 1.4 [7]:

$G=exp\left[\left\{Γ\_{g}-α\right\}L\right]$ 1.4



Fig 1.2 Structure of semiconductor optical amplifier

where Γ is optical confinement factor that guides photons through the active layer; g is the gain coefficient of active layer per unit of length and α is the loss coefficient of active layer per unit of length. In addition to this gain coefficient (*g*) depends on the frequency *(ω)* and power of the signal being amplified (*P*) [7]. Thus *g=g (ω, P)* is given by equation 1.5

*g(ω,P) = g(ω)/[1+ (P/ Psat )]* 1.5

This is for bulk active layer and the active layer is of isotropic spherical quantum dot type. In general due to its three dimensional quantization, quantum dot active layer exhibits a discrete gain peak. *The main reason behind the output power saturation is the reduced population inversion which is caused by the intense input optical power that consumes the population inversion carriers.* Saturation power is given by equation 1.6 [7]:

$P\_{s}=Cωℏ\frac{dω}{Γ}\frac{1}{g\_{d}τ}$ 1.6

where *C* is the fiber to chip coupling efficiency, *d* is the thickness of active layer, w is the width of active layer, *Γ* is the optical confinement factor, *gd* is differential gain,$ τ$ is carrier lifetime and *dω/Γ* represents the mode cross-section. Large saturation power can be obtained by optimizing the design of the active layer, optical confinement factor and carrier lifetime. If the width of the active layer is reduced, it gives a small loss to the TE mode as compared with that for the TM mode, resulting in polarization dependence. Research on the design of active layer for minimizing polarization dependence is in progress. At present SOA with bulk active layer is the most suitable to achieve large saturation power and polarization insensitive response [7-10]. The nonlinear optical effects in SOAs are

**Cross gain modulation** According to the homogenously broadened material gain spectrum of SOA, the change in carrier density inside the amplifier will affect the input signals, thus it is possible for a strong signal at one wavelength to affect the gain of a weak signal at another wavelength. This non-linear mechanism is called cross gain modulation (XGM). The CW probe signal and a pump / control signal are injected into SOA [7] as shown in Fig 1.3. Due to XGM in the amplifier pump signal modulates the probe signal. And hence the probe signal at the output will carry the same information as the input pump / control signal and the system will act as a wavelength converter [11].



 Fig. 1.3: wavelength converter using XGM in SOA [14].

 

1. (b)

Figure 1.4. (a)Probe pulse before passing through SOA and (b) the gain of probe increases after passing through SOA as shown with black shade



1. (b)

Figure 1.5(a). *Effect of XGM on pump and probe pulse before passing through SOA, (b) Probe and pump after passing through SOA*

The information in pump signal will be transferred to probe signal i.e. carrier signal. The most useful figure of merit of this converter is the conversion efficiency, defined as the ratio between the powers of the output probe to the power of the input pump. The wavelength conversion techniques based on semiconductor optical amplifiers (SOA) are attractive because of their high-gain, high saturation output power, wide-gain bandwidth, compactness, and compatibility with other photonic devices.

The cross gain modulation (XGM), one of several wavelength conversion techniques based on SOAs, is simple to implement and can be used for high bit rate. Moreover, the output of optical computing devices using XGM in SOA is almost polarization insensitive [11-14]. Cross gain modulation (XGM) occurs due to gain saturation in SOA. The simplest approach of XGM is shown in Fig 1.4 and 1.5. When light of two different wavelengths, pump and probe pass through SOA, operated under the gain saturation condition, the total available gain is distributed between the two wavelengths of pump and probe pulses. The distribution of gain depends on their relative photon densities.

**Self-phase modulation** (SPM) The nonlinearity in SOA also produces a carrier induced phase modulation of the propagating signal, which is known as Self Phase Modulation (SPM). The physical mechanism behind SPM is gain saturation, which leads to intensity-dependent changes of refractive index due to variations in carrier density. Gain saturation in SOA is caused by reduction of the population inversion due to an increase in stimulated emission. Gain saturation characteristics are especially important in optical repeaters and multi-channel amplifiers because they require high-power operation. is used to design all-optical computing devices meant for buffering and delaying signal pulses. Tunable all-optical delays are important for application in telecommunication, optical coherence, optical sampling etc. Single channel nonlinear effect is mainly through SPM i.e. each channel alters its own phase. When there is more than one signal, the phase and gain of each signal is modified by the power of neighboring channel also, these phenomena are XPM and XGM respectively.

**Cross phase modulation** (XPM) occurs as a result of Kerr effect. The refractive index of SOA active region is not constant but it depends on the carrier density and frequency of the incident light. This implies the phase and gain of the optical wave propagating through SOA, is coupled. In XPM, if more than one signal is injected into a SOA simultaneously in interferometer configuration, the phase modulation is converted into intensity modulation. The refractive index of the active region of SOA is not constant but is dependent on the carrier density and hence on the material gain [14]. Both the phase and gain of an optical wave propagating through the SOA are affected by gain saturation. If more than one signal is injected into SOA, there will be cross-phase modulation (XPM) between the signals. XPM can be used to create wavelength converters and other functional devices. However, because XPM only causes phase changes, the SOA must be placed in an interferometric configuration to convert phase changes to intensity changes using constructive or destructive interference. In XPM, phase shift depends on wavelength, effective area and variation in pulse power with time. For designing ultra-fast optical computing devices using XPM, many interferometric methods have been used. Thus, in an interferometer a control signal pulse is divided equally between its two arms. When a probe pulse at different wavelength is injected into one of the arms, it will change the signal phase through XPM phenomenon in that arm. If the XPM-induced phase shift is close to $π$ it results in destructive interference and hence no transmission of signal pulse. Thus switching takes place.

**Four-wave mixing** (FWM) generated in SOA can be used in many applications including wavelength converters, dispersion compensators, optical demultiplexers and other optical logic devices. It is a coherent nonlinear process that occurs in SOA. When optical signals at different wavelengths merge into SOA then new signals at other wavelengths are produced as shown in Fig 1.5. It is generated by the intensity-dependent refractive index of silica medium. When carrier density modulates the non-linear gain in SOA, it causes a change in refractive index. This produces a phase shift within a channel and generates a new signal at different frequencies. When two optical fields, CW probe signal at angular frequency ω and a data / control signal at angular frequency (ω – Ω), having the same polarization are applied to the input of SOA. The injected fields cause the amplifier gain to be modulated at the beat frequency Ω. This gain modulation gives rise to a new field at ω + Ω, [14]

 signal Probe conjugate signal

signal (ω-Ω)

SOA

CW probe(ω)

 ω -Ω ω ω +Ω

 output spectrum

Fig.1.5: Four wave mixing in SOA [14].

**Cross polarization modulation** (XPolM) is closely related with cross phase modulation, they originate almost in the same form. The phase modulation component which is polarization independent corresponds to cross phase modulation (XPM) and the component which is polarization dependent corresponds to cross polarization modulation. XPolM effect occurs when a signal with a known state of polarization is injected into an SOA. Polarization at the output of the device gets changed. This rotation in the state of polarization is a nonlinear effect and may be used to perform all-optical signal processing functions. Nonlinear polarization rotation in the SOA is caused due to waveguide asymmetry in the device mainly. If the device is not perfectly symmetric, the confinement factor Г is different for the Transverse Electric (TE) and Transverse Magnetic (TM) Modes. This results in polarization dependence of the device gain as given by equation 1.7. Asymmetry in waveguide also introduces birefringence, which causes two propagation constants to exist corresponding to the orthogonal TE and TM modes. The effective refractive indices will differ for the two and the typical difference is 2x10-2 [15]. The difference in refractive index causes the TE and TM modes to propagate through the device at different speeds resulting in a phase difference to be introduced between the signals. An index difference of around 2x10-4 is sufficient, to introduce a phase shift of 90o between the TE and TM modes [16]. The overall device gain is generally larger for the case of TE polarization. The difference in gain for the two modes can be minimized by designing a completely square waveguide [17]. To design a completely square waveguide, a technique generally used is to introduce tensile strain to enhance the Light-Hole (LH) transitions, and therefore the TM transitions. In this way the TM gain is increased to a level where it compensates for the higher TE gain. This minimizes the difference in gain between TE and TM axes. This balancing of the gains can be understood by considering the following expression [18]:

$∆G\_{TE-TM}\left(dB\right)=\left⌈1-\left(\frac{Γ\_{TM}}{Γ\_{TE}}\right)\left(\frac{g\_{TM}}{g\_{TE}}\right)\right⌉G\_{TE}\left(dB\right)$ (1.7)

 where GTE/TM represents the modal gain, ГTE/TM represents the confinement factor and gTE/TM represents the material gain for TE and TM mode respectively. From this expression it is clear that increasing gTM over gTE can compensate for the larger confinement along the TE axis. Although complete polarization insensitivity has never been achieved, it is an effective technique in compensating for the higher TE gain [18]. Being a part of Cross Phase modulation, its applications will be similar to that of Cross Phase Modulation.

While using SOA for ultrafast signal processing, the most inconvenient feature is the slow response due to inter band carrier recombination. There are two methods to overcome this slow response. One is to select the ultrafast response and reject the slow response by using a wavelength filter[19-24]. The other is the use of SOA in Mach–Zehnder Interferometer configuration with SOA in each arm. This method uses differential modulation scheme to cancel out the slow response component and pass the ultrafast component. In both these configurations nonlinear optical effects associated with the carrier density change in SOAs are utilized.

Optical filtering at the output of SOA to select only the ultrafast component is a powerful technique and has been utilized frequently to enhance the modulation bandwidth of SOA-based optical computing devices. This method has been successfully used for all optical wavelength conversions at 10, 40, 80,160, and 320 Gb/s [19-23], and optical demultiplexing from 320 to 40 Gb/s [24]. In an all-optical switch based on a SOA followed by an optical band-pass filter, injected control signal alters the gain and refractive index of the SOA. This results in Intensity modulation of the co-propagating CW probe light. The leading and trailing edges of the intensity modulated probe light are red and blue shifted, respectively. Frequency of the Band Pass filter is selected such that the control signals are rejected by the BPF, while a part of the probe light is transmitted. When the BPF is detuned towards the shorter wavelength (blue shift) with respect to the probe light, the Intensity modulated signal recovers much faster than in the absence of the BPF [7] Fig. 1.6 shows an all-optical switch based on a SOA followed by an optical band-pass filter. Short optical pulses are injected into the SOA as a control signal along with a CW probe light.

Control signal

 Output at probe light wavelegth

probe light

Filter

SOA

Fig 1.6 All-optical switch based on SOA followed by an optical Band-pass filter [7].

Wavelength conversion has been demonstrated for bit rates up to 320 Gb/s. Crossgain modulation based wavelength-converted RZ signal is inverted. Thus notch filters that suppress the DC component were used after BPFs to obtain non inverted data signals. Notch filters were realized using polarization interferometers. Using the similar principle, all-optical demultiplexing was demonstrated in which 320 Gb/s optical time-division-multiplexed (OTDM) data stream was demultiplexed into 40 Gb/s base-rate channels [24]. One of the advantages of SOA based optical switches with optical BPFs is their simple configuration that makes it compatible for integration with other devices. In addition to the above, many optical computing devices using SOAs followed by optical BPF have been reported in recent years, like reconfigurable optical logic gates were realized which are based on various nonlinearities in single SOAs [25] all-optical flip-flop using SOAs with optical feedback has been proposed, [26] all optical half adder design using XGM and FWM effect in SOAs have been reported, [27] and NAND gate, flip-flop, and finally three input serial shift register have been demonstrated [28].

In SOA-MZI configuration based wavelength converter, SOAs used as nonlinear waveguides are placed in both arms of Mach–Zehnder interferometer. The control light governs the dynamics of nonlinear optical effects and the probe light experiences the nonlinear optical effects. The control light can be either return-to-zero (RZ) or non-return-to-zero (NRZ) light pulses. The SOA-MZI set up shown below uses both the control light and the probe light of RZ form. In SOAs, the control pulse induces carrier depletion and thus modulates the gain and phase of the probe light. These phenomena are called cross-gain modulation (XGM) and crossphase modulation (XPM) respectively. [30-33]

 **γ 1-γ**

**CW probe(λ2) input signal(λ1)**

 **Converted signal (λ2)**

 **1-γ γ**

**SOA**

**SOA**

(a)

 **Input signal (λ1)**

 **γ γ**

**control probe (λ2 ) converted**

 **signal(λ2)**

 **γ γ**

**SOA**

**SOA**

(b)

Fig. 1.7 wavelength converter based on SOA-MZI Configuration in (a)asymmetric and (b)symmetric form [7].

The nonlinear optical effects XPM and XGM used in these wavelength converters are induced through the carrier density change in semiconductors and are highly efficient in terms of size and low power requirement. Further due to amplification in SOA, the requirement of power for control signal is again reduced. The major obstacle in using XGM and XPM with the carrier density change in SOAs is its slow recovery time due to band to band recombination. Typical value of this slow recovery time lies in the range of 100 ps to 1 ns [7]. The effect of this slow recovery is canceled out in the SOA-MZI configuration by introducing appropriate time delay and arranging SOAs symmetrically. The dynamics of carrier density in SOAs and associated nonlinear optical effects can be analyzed by rate eqns. [7]

$\frac{dN}{dt}=J-\frac{N}{τ}-g\_{d}\left(N-N\_{tr}\right)\frac{S\_{c}}{ℏω\_{c}}-g\_{d}\left(N-N\_{tr}\right)\frac{S\_{P}}{ℏω\_{P}}$ 1.8

$\frac{dS\_{c}}{dz}=Γg\_{d}\left(N-N\_{tr}\right)S\_{c}-aS\_{c}$ 1.9

$\frac{dS\_{p}}{dz}=Γg\_{d}\left(N-N\_{tr}\right)S\_{p}-aS\_{P}$ 1.10

where N is the carrier density, J is the rate of carrier injection through bias current, Ntr is the transparency carrier density, Sc is the control light power, Sp is the probe light power, ωc is the control light frequency, ωp is the probe light frequency, gd is the differential gain, is the carrier lifetime, Γ is the light confinement factor, and a is the optical loss coefficient including absorption and scattering. The phase shift is proportional to the total carrier number in SOA i.e. integral of N along the entire length of SOA. In fact, there are various configurations that utilize the mechanism of canceling out the relaxation tail of carrier density change. One of the important points for categorizing these configurations is whether the control light and the probe light are co-propagated or counter-propagated through the SOAs. When the probe light is counter propagated with the control light, the gate window shape is influenced by the time during which the control light propagates through the entire length of the SOA.[34,35].

When the input power injected into SOA increases, the maximum of the output power will be moved towards the high wavelength, gain maxima i.e. peak of the gain is moved towards the high wavelength due to decrease of the carrier’s density, SOA gain decreases as the input power is increased due to gain saturation. One of the main reasons behind gain saturation in SOA is depletion of carrier density owing to stimulated emission. Besides this, gain saturation is also caused by Spectral hole burning (SHB) and Carrier heating (CH). It had been noted by analysis of characteristics of SOA that small input power with high injection current can minimize the noise effect. In a general analysis of the devices using SOAs, the influence of amplified spontaneous emission (ASE) is also important[38,39]. However, in the situations considered here for all-optical signal processing/computing, control light highly depletes carriers in SOAs and hence neglecting the effect of ASE, still gives good approximation to the carrier dynamics of SOAs. [23]

Some important all optical devices like buffer and OR gate using SOA-MZI [34] inverter using SOA-based Mach–Zehnder interferometer[35], NOR gates using SOA based MZI [36] AND, XOR and OR gates based on SOA-MZI configuration [37] have been simulated and reported.

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