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

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**Abstract**

**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. The wavelength conversion, logic functions, optical signal representation are the key to achieve all optical signal processing. For these functions the non-linear optical device is to be used i.e. Semiconductor Optical Amplifier (SOA). Due to its compact size, gain, low response time, refractive index difference, easy to integrate, and power efficient, SOA has proved to be the promising device to be used in optical signal processing.**

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

1. **Introduction**

The internet traffic on the network is increasing every day which is causing problem of power consumption. Transmission of data from one end to another and switching of data at each node for routing of data are the two basic functions of the network. The switching are: circuit switching and packet switching. In circuit switching in optical domain, the power consumption increases with increase in number of wavelengths. The communication networks have become more internet protocol (IP) based thus optical circuit switching consumes more power thus Optical Packet switching is more in use now. The input alignment, buffering, wavelength conversion are required to switch the packet to the required output port. Advanced all-optical signal processing functions like header recognition, buffer, switching, wavelength conversion, logic functions, storage etc need to be realized.

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.

When electric field/light is applied on the material, its bound electrons start vibrating harmonically is called non-linearity and the materials which on interaction with electric field/ light modulate its properties are called non- linear materials. Efficient nonlinear materials are needed. Many nonlinear materials available required large amount of energy for responding thus they are not used in optical computing.

Non-linear optical effects usually help in all optical computing. Optical computing is developing in two ways [1]. Either the hybrid computers are built to use today’s computer architecture or to build all optical computer that performs all functions like optical logic gates, optical switches, optical interconnections and optical storage devices in optical domain .

1. **Nonlinear Effects in Optical Fiber**

Nonlinear effect in silica glass is lower than other nonlinear materials. Second-order susceptibility does not contribute for nonlinear response as silicon dioxide has no inversion symmetry. The nonlinear effects in Silica fiber are due to third order only and its value for silica glass is smaller than crystals and liquids [2].

The fiber based optical computing devices are easy to couple to the transmitting fiber and coupling losses decrease, the nonlinear effects are very fast thus processing happens very fast i.e. in femtoseconds beyond 1 Tb/s and no noise is added to the signal in the processing due to its passive nature. The high nonlinear fiber are used due to high conversion bandwidth, low attenuation, larger Raman gain coefficient, shift of zero dispersion wave length, optical fiber system compatibility [3]. Nonlinear Effects in Optical Fiber can be classified into two as given in Table1.1

**Table 1.1 Classification of non- linearity in optical fiber**.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 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 |

The optical power from one mode is transferred in either the forward or backward direction to the same or other modes at different frequency when nonlinear scattering occurs. It depends on the optical power density and become significant as cross thresholds. At high optical power densities in long single-mode fibers the nonlinear scattering i.e. stimulated Brillouin and Raman scattering are seen. It gives optical gain with a little shift in frequency.

**(i).Stimulated Brillouin scattering (SBS)**: Stimulated Brillouin Scattering in the fiber is due to thermal molecular vibrations. The modulated light gets scattered and appears as upper and lower sidebands with incident light. In this scattering, an acoustic phonon with scattered photon is produced. It is also known as backward process because the shift in frequency is maximum in backward direction.

**(ii) Stimulated Raman Scattering (SRS)**: In this scattering process the high frequency optical phonon rather than an acoustic phonon is produced. It occurs both in directions. The acoustic phonons generated bu Brillouin are coherent and form an acoustic wave while the optical phonons generated by Raman scattering are incoherent..

**(iii) Self-phase modulation (SPM):** The refractive index of medium varies with the variation in intensity of signal. The variation in refractive index with intensity of signal is given in equation 1.1 [3].

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

where *Aeff* is the effective core area, *P* is the optical power *n0* and *n2* are refractive index of the material and is the nonlinear index coefficient respectively. The back of pulse*)* and front of pulse experiences a positive and negative refractive index gradient and this phase variation as shown in Fig 1.1.



Fig.1.1: Pulse broadening due to self-phase modulation [3].

The variation in optical signal is given by phase variation. It is non-linear and self-induced thus self-phase modulation. γ is the magnitude of the SPM nonlinear effect [3] and given by equation 1.2

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

 λ is free space wavelength. As the refractive index change is intensity dependent thus different parts of the pulse undergo different phase shift and results in phase fluctuations that form frequency chirping. The leading edge of the pulse shifts in upper side whereas the trailing edge experiences shift in lower side. The spectrum of the pulse broadens due to SPM with unaltered pulse shape. The chirping effect is high in high transmitted signal power so the SPM is also. 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, The high power is launched into the fiber to increase the repeater spacing. SPM effect is seen as it crosses the threshold and results in pulse spreading. The SPM effect is reduced using large effective area fiber (LEAF) as it reduces the intensity inside the fiber.

**(iv) Cross phase modulation (XPM):** The XPM is accompanied with SPM when more than one optical pulse propagates simultaneously because the nonlinear refractive index depends on the input beam intensity and co- propagating beam intensity. It changes power fluctuations in one wavelength channel to phase fluctuations to co-propagating channels resulting in broadening and distortion of the pulse shape. It affects performance as SPM i.e. chirping frequency and chromatic dispersion. The system performance is damaged more than SPM. As number of channels increases the damage increases. XPM imposes a power limit of 0.1mW per channel for hundred channel system [4]. By using non-dispersion shifted single mode fiber the effects of XPM can be minimized. The XPM depends on interaction length and cross sectional area of fiber. The long interaction length builds it to a significant level and use in all-optical computing devices. The induced phase shift Δφ [3] is given by equation 1.4

$Δϕ=\frac{dφ}{dt}=2γL\_{eff}\frac{dP}{dt}$ 1.4

The total phase shift is the sum of the phase shifts due to SPM and XPM effects for all the wavelengths.

**(v) Four wave mixing (FWM)** Due to third order nonlinear susceptibility (χ(3)) in fiber, the FWM arises. The three optical fields with carrier frequencies ω1, ω2 and ω3 when co-propagate inside the fiber at the same time, the fourth field with frequency ω4 is generated and is given by equation 1.5. $ω\_{4}=ω\_{1}\pm ω\_{2}\pm ω\_{3 }$ 1.5

The FWM effect is independent of the bit rate but depends on the channel spacing and fiber dispersion though SPM and XPM affect high bit rate systems. As the channel spacing and dispersion decreases, the four-wave mixing effect increases. The WDM system with dispersion shifted fiber (DSF), the FWM poses severe effect and this effect can be minimized by changing the channel spacing and dispersion of fiber. The dispersion varies with wavelength. The efficiency of FWM is reduced because of chromatic dispersion, thus DSF is used.

**Limitation**

The larger length of fiber is required to produce a significant amount of nonlinear effect that could be used in all optical computing and the switching energy required for any switching operation in fiber based devices is higher to that of SOA based devices*.*

1. **Nonlinear organic materials**:

Organic semiconductors are carbon materials like polyaniline (PAn), polyparaphenylene (PPP), polyparaphenylene, vinylene. They are broadly categorised into two. First, the organic molecule semiconductors (OMS) having lower molecular weight and are deposited using thermal evaporation in high vacuum environment and second is polymeric organic molecule having long chain of organic molecules processed from solution. High nonlinearities and flexibility of molecular structure made organic materials popular for all optical computing devices.[4] The initial challenges in production of high performance air-stable organic materials are solved and now they can exhibit speed performance, stability and uniformity of parameters over large-areas comparable to those of a Si Thin Film Transistor like phthalocyanines and polydiacetylenes for all-optical logic gates [1]. These photosensitive organic material very useful for photovoltaic, photoconductive, and photo electrochemical applications [1]. The organic compounds are promising components for optical thin films and waveguides. Third order susceptibility of phthalocyanine is very high and the nonlinear property of Polydiacetylenes can be used for all-optical switching and high-speed optoelectronics applications.[1]

1. **Semiconductor Optical Amplifier (SOA)**

The parameters like high gain, high saturation output power, wide gain bandwidth, compactness and integration of SOA based all optical computing devices make them very attractive. The only limitation is their polarization dependent characteristic that gives pattern effect. The basic structure of SOA is the similar to that of semiconductor laser diodes without antireflection coating. The basic structure of a semiconductor optical amplifier is given in Fig. 1.2 [6].

The active layer (bulk, quantum well or quantum dots) with lower energy band gap is sandwiched between the semiconductor layers. When forward voltage is applied, free electrons from the n-type material and holes from the p-type material travel towards the active layer and get 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 achieved by appropriate pumping and stimulated emission occurs. the stimulated emission dominates the stimulated absorption as sufficient population inversion is achieved and light is amplified [6]. The gain of an amplifier is expressed by the following equation 1.6 [7]:

$G=exp\left[\left\{Γ\_{g}-α\right\}L\right]$ 1.6



Fig 1.2 Structure of semiconductor optical amplifier

where g, α is the gain and loss coefficient of active layer per unit of length and Γ is optical confinement factor. This gain coefficient (*g*) depends on the frequency *(ω)* and power of the signal (*P*) [7] and is given by equation 1.7

*g(ω,P) = g(ω)/[1+ (P/ Psat )]* 1.7

This equation is for bulk active layer but quantum dot active layer exhibits a discrete gain peak due to 3d quantization beacause output saturated power is the reduced due to population inversion. Saturation power is given by equation 1.8 [7]:

$P\_{sat}=Cωℏ\frac{dω}{Γ}\frac{1}{g\_{d}τ}$ 1.8

where $ω, d$ are the width and thickness of active layer, *Γ* is the optical confinement factor, *gd* is differential gain,$ τ$ is carrier lifetime and *C* is the fiber to chip coupling efficiency. By optimizing the design of the active layer, confinement factor and carrier lifetime large saturation power can be achieved. [7-10].

If the input power injected into SOA is increased, the gain decreases and gain peak is towards the higher wavelength. The gain decreases due to gain saturation in SOA. The gain saturation is due to depletion of carrier density owing to stimulated emission and also caused by Spectral hole burning (SHB) and Carrier heating (CH).

. The carrier density dynamics and nonlinear optical effects associated are given by eqns ( 1.9-1.11). [7]

$\frac{dN}{dt}=J-\frac{N}{τ}-g\_{d}\left(N-N\_{tr}\right)\frac{S\_{c}}{ℏω\_{c}}-g\_{d}\left(N-N\_{tr}\right)\frac{S\_{P}}{ℏω\_{P}}$ 1.9

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

$\frac{dS\_{p}}{dz}=Γg\_{d}\left(N-N\_{tr}\right)S\_{p}-aS\_{P}$ 1.11

where Sc,Sp are the control light and probe light power, ωc, ωp are the control and 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 N, Ntr is the carrier and transparency carrier density, J is the rate of carrier injection through bias current.

The inconvenient feature of using SOA is the slow response because of inter band carrier recombination. To avoid this slow response there are two ways either to select the ultrafast response by using a wavelength filter and the modulation bandwidth of SOA-based optical computing devices is enhanced.[11-16] or cancel out the slow response component using differential modulation and pass the ultrafast component using SOA in Mach–Zehnder Interferometer configuration with SOA in each arm i.e. SOA-MZI. The nonlinear optical effects associated with change in carrier density in SOAs are used Fig. 1.3 shows an all-optical switch based on a SOA followed by an optical band-pass filter. The input control signals changes the gain and refractive index of the SOA and modulates the intensity of the co-propagating CW probe light. The band pass filter is selected at such that the probe light is transmitted and the control signal is rejected.

Control signal

 Output at probe light wavelength

probe light

Filter

SOA

Fig 1.3 SOA based All-optical switch based using optical Band-pass filter [7].

SOA based optical switches with optical BPFs has an advantage of simple configuration and its compatiblity of integration. All-optical flip-flop using SOAs with optical feedback, [17] all optical half adder design using XGM and FWM effect in SOAs, [18] and NAND gate, flip-flop, three input serial shift register [19] are proposed, demonstrated and reported. SOAs are used as nonlinear device and placed in both arms of Mach–Zehnder interferometer. The nonlinear optical effects occur due to control signal and they are experienced by probe signal. The SOA-MZI shown in Fig 1.4 uses both the control light and the probe light. The carrier depletion is induced by control signal and gain as well as phase of the probe signal is modulated using XPM and XGM [20-24]

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

The nonlinear optical effects in SOAs are

**Cross gain modulation**: The inputs to SOA are pump / control signal and a CW probe signal [7] as shown in Fig 1.5. Due to XGM the probe signal gets modulated by the pump signal. The strong signal at one wavelength affects the gain of a weak signal at another wavelength. This non-linear mechanism is called cross gain modulation (XGM). Cross gain modulation (XGM) occurs due to gain saturation in SOA. Thus, the modulated probe carries the same information as the input pump signal and the system acts as a wavelength converter [11]

Pump filter

CW probe Modulated probe

**SOA**

Fig. 1.5: Wavelength converter using XGM in SOA [14].

The gain distribution depends on density of photons. Probe signal is the carrier signal and the data or information in pump signal is transferred to carrier. The figure of merit is the ratio of the powers of the output probe to the input power. The SOA is compatible and integrable with other photonic devices. The SOA based wavelength converters have high and wide band gain. Cross gain modulation (XGM) occurs due to gain saturation in SOA. The simplest approach of XGM is shown in Fig 1.6 and 1.7. 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. Due to its simplicity and implementation at high bit rate, it is really attractive. The devices using XGM are insensitive to polarization. [25-28].

 

1. (b)

Figure 1.6. (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 1.7(a). *Effect of XGM on pump and probe pulse before passing through SOA, (b) Probe and pump after passing through SOA*

**Self-phase modulation** **(SPM):** The modulation in phase of propagating signal when induced by probe (carrier) due to non-linearity in SOA is called Self Phase Modulation (SPM). Due to light intensity the gain saturates and the carrier density changes that gives change in refractive index. The increase in stimulated emission reduces population inversion that saturates the gain. This gain saturation requires high power and has application in repeaters and amplifiers. SPM is used to design all-optical buffer, Optical coherence, sampling and tunable all-optical delays have applications in telecommunication,

**XPM and XGM** happen when two or more signals are there: the phase and gain of a signal is modified by neighboring one respectively. The control signal is the modulating signal hat induces carrier depletion and modulates the gain and phase of probe/ carrier signal. In XGM data pulse at wavelength (λ1) modulates the carrier density in SOA and clock pulse injected into the SOA at the same time as shown in Figure 1.4. The carrier density gets modulated and gain of the pump signal (λ1) gets compressed producing chirp of the converted signal. The SOA in an interferometer configuration converts this phase change into an intensity modulation utilizing the chirp of converted signal using constructive or destructive interference. The phase shift depends on wavelength, effective area and variation in pulse power with time. The high optical intensity is used in SOA to reduce the gain recovery time. The wavelength converters are designed using XPM and XGM. The problem related to XGM is at longer wavelength the extinction ratio is penalized. To obtain a complete extinction in an interferometer a phase shift of π is needed as in Figure 1.4 which can be achieved with gain compression in SOA. The phase shift is independent of wavelength, so the conversion to a longer wavelength has no problem with XPM. The disadvantage of an interferometer structure is that, if the phase shift increases more than π, it impairs the extinction ratio which may be controlled by changing the bias condition of SOA. The interferometer configuration may be defined in two ways, co-propagation and counter-propagation. In co-propagation, filter is required because pump and probe travel in the same direction to filter the probe signal with pump. But in counter-propagation both travel in opposite directions, so the filter is not required.

In **FWM** two signals are input into the SOA at two different wavelengths. Due to the difference in frequency modulated signals in SOA, change in intensity occurs called beating. If the frequency separation is small the carrier density will be modulated and if larger the moving grating in the active layer strip of SOA is set due to modulated carrier. The sidebands at the lower and higher frequency are produced and their power is usually less as compared to the signal power as in Figure 1.8. The optical signal at different wavelengths when merges into SOA and produce new signals at other wavelengths. The carrier density modulates the non-linear gain thus refractive index changes and 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 ω1 and a data / control signal at angular frequency (ω2 – ω 3), 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 3 This gain modulation gives rise to a new field at ω2 + ω 3, [28] FWM depends on the phase of the optical signal instead of Intensity thus it is more polarization dependent phenomenon implying that all optical network schemes do not use FWM but has application in managing dispersion by optical phase conjugate. [29].

 signal Probe conjugate signal

signal (ω2-ω3)

SOA

CW probe(ω1)

 ω 2 - ω 3 ω1 ω 2+ ω 3

 output spectrum

Fig.1.8: Four wave mixing in SOA [14].

**Cross polarization modulation**. The change in the state of polarization is a nonlinear effect. Nonlinear polarization rotation in the SOA happens due to asymmetry in the device. When it is not perfectly symmetric, the confinement factor Г for the Transverse Electric (TE) and Transverse Magnetic (TM) Modes (i.e birefringence) will be different that results in dependence of device gain on polarization and phase shift of 900 is introduced. [30,31]. It can be minimized by designing square waveguide [32,33].

The nonlinear optical effects XPM and XGM used in these wavelength converters are induced through the carrier density change in semiconductors. The categorization of different designs is based on whether the control light and the probe light are co-propagated or counter-propagated. [34,35]. 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 have been simulated and reported. The small input power with high input current can minimize the noise effect at SOA. The influence of amplified spontaneous emission (ASE) is also important[36-39] but for all-optical signal processing the control light highly depletes carriers in SOAs and hence the effect of ASE is neglected. [7,23]

1. **Conclusion**

Tremendous development in all-optical SOA based devices have been achieved in the last decade. It is necessary to build all-optical devices that can be controlled optically and easily integrated on a photonic chip. For all-optical functions wavelength conversion, multiplexing, clock recovery, regeneration and bit pattern recognition are needed.

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