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A Review on Nonlinearity in Semiconductor optical Amplifer as Application in all Optical Signal Processing

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Abstract

The optical signal processing is the future of communication network. High speed all-optical packet routing is one of the essential applications of all-optical networks which is only possible with the development of all-optical logic technology. The development of optical logic elements and circuits are the steps in the growth of this technology and higher speed up to Tbit/sec can be achieved. The optical carrier frequency range 10^{13} to 10^{16} 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 non-linear optical device to be used *i.e.* Semiconductor Optical Amplifier (SOA) has proved to be the promising for all optical functions like wavelength conversion, logic functions, signal representation in all optical domain. Its compact size, high gain, fast response, strong refractive index variation, easy to manufacture and integration, and power efficiency makes it most optimum device for optical signal processing. In this paper, the application of SOA in optical processing is thoroughly reviewed and orient towards the latest application in neural networks.

Key words : optical signal processing, opto-electronic conversion, all optical switching.

I. 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. For optical packet switching alignment of input, buffering, wavelength conversion are required to switch the packet to the required output port. The advanced functions like all-optical header recognition, buffer, switching, wavelength conversion, logic functions, storage etc can 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 or 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 or light modulate its properties are called non- linear materials. Efficient nonlinear materials are required for their operations. but the non-linear materials that large amount of energy to respond are not used in optical computing.

Non-linear optical effects usually help in all optical computing. Two ways to develop this field[1] either building hybrid computers so that the last technology can use optics for some functions or to build all optical computer that perform all functions in optical domain.

II. 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 with smaller value for silica glass is smaller than crystals and liquids[2].

Optical fiber based optical computing devices has numerous advantages i.e. they can be easily coupled to the transmitting fiber this coupling losses decrease, the nonlinear effects are very fast thus processing happens very fast *i.e.* in femtoseconds beyond 1 Tb/s and without any addition of noise due to its passive nature. 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 (3). Nonlinear Effects in Optical Fiber can be classified into two as given in Table 1.1. The first highly nonlinear fiber (HNLF) was developed by Nippon Telegraph and Telephone Corporation (NTT) in 1986. Sumitomo Electric Industries, Ltd. demonstrated a dispersion-shifted HNLF with a zero-dispersion wavelength of 1.55 µm in 1997, and opened to nonlinear applications in all optical signal processing[4,5]. Photonic crystal fiber are used in ultra- fast optical signal processing[3]. The nonlinear scattering depends on optical power density and become significant at thresholds. As nonlinear scattering the optical power is transferred from one mode to the same or other modes in either the forward or backward direction at different frequency. The nonlinear scattering i.e. stimulated Brillouin and Raman scattering are seen at high optical power densities in long single-mode fibers. These scattering gives optical gain with a shift in frequency.

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

.

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

(ii) Stimulated Raman Scattering (SRS)*:* Stimulated Raman 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 Brillouin generated phonons i.e. acoustic phonons are coherent and form an acoustic wave in the fiber, while in Raman scattering the optical phonons are incoherent and no acoustic wave is generated.

(iii) Self-phase modulation (SPM): The major nonlinear effect in a single fiber is 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].

$$n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{eff}} \qquad 1.1$$

where n_0 is the initial refractive index of the material and n_2 is the nonlinear index coefficient, P is the optical power and A_{eff} is the effective core area. The leading edge experiences a positive refractive index gradient *(dn/dt)* and trailing edge experiences a negative refractive index gradient *(–dn/dt)* and this variation causes variation in phase, as shown in Fig 1.1.

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

$$\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{eff}} \qquad 1.2$$

λ is free space wavelength. As the change in refractive index depends on intensity thus the pulse undergoes phase shift that 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

$$\Delta\phi = \frac{d\varphi}{dt} = \gamma L_{eff} \frac{dP}{dt} \qquad 1.3$$

where L_{eff} 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.

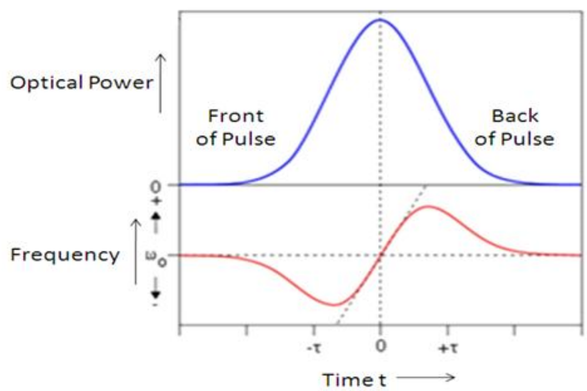


Fig. 1.1: Spectral broadening of a pulse due to self-phase modulation[3].

(iv) Cross phase modulation (XPM): The XPM is accompanied with SPM when more than one optical pulse propagates simultaneously because the nonlinear refractive index does not only depend on the intensity of the beam but also on the intensity of co- propagating beams. It converts power fluctuations at a particular wavelength channel to phase fluctuations in other co-propagating channels resulting in asymmetric spectral broadening and pulse shape distortion. The system performance is affected similar as SPM i.e. chirping frequency and chromatic dispersion. But the damages is more than due to 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. XPM depends on interaction length of fiber and cross-sectional area like SPM. These effects builds up to a significant level due to long interaction length. The induced phase shift Δφ [3] is given by equation 1.4.

$$\Delta\phi = \frac{d\varphi}{dt} = 2\gamma L_{eff}\frac{dP}{dt} \qquad 1.4$$

The sum of the phase shifts due to SPM and XPM is the total phase shift for all the wavelengths. The high bit rate systems are effected by SPM and XPM

(v) Four wave mixing (FWM) Due to third order nonlinear susceptibility ($\chi(3)$) in fiber, the FWM arises. The three optical fields with carrier frequencies ω_1, ω_2 and ω_3 when co-propagate inside the fiber at the same time, the fourth field with frequency ω_4 is generated and is given by equation 1.5.

$$\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3 \qquad 1.5$$

FWM is independent of the bit rate but depends on the channel spacing and fiber dispersion. The effect of four-wave mixing increases as the channel spacing and dispersion decreases. 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 :

To produce a significant amount of nonlinear effect, the larger length of fiber is required. To perform the switching operation in fiber based devices the higher energy required in fiber based devices as compared to that of SOA based devices.

III. 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. Due to their high nonlinearities and flexibility of molecular design, organic materials have become popular among 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 have been used for designing all-optical logic gates[1]. These materials are used as a photosensitive organic material in photovoltaic, photoconductive, and photo electrochemical applications[1]. The organic compounds are promising components for optical thin films and waveguides. Organic materials have become popular among all optical computing devices due to high nonlinearities of third order and flexibility of molecular design, Due to the nonlinear properties of Polydiacetylenes, they can be used for switching in all-optical domain and among the most significant polymers for nonlinear optical applications. Their suitability for high-speed optoelectronics applications is due to their high response time to laser signals[1].

IV. Semiconductor Optical Amplifier (SOA) :

The parameters like gain, 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. On application of forward voltage the 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. 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 1.6 [7] :

$$G = exp\left[\{\Gamma_g - \alpha\}L\right] \quad 1.6$$

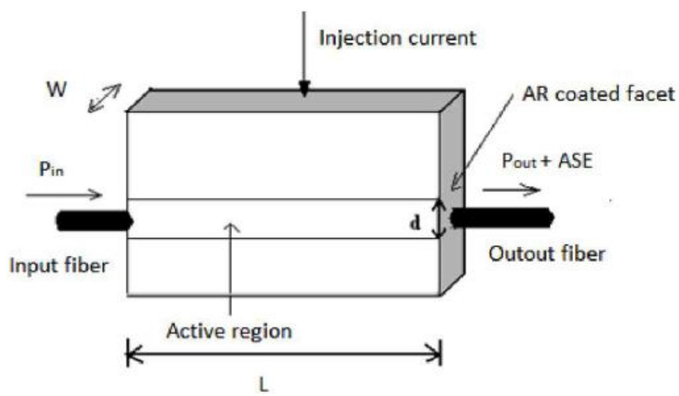


Fig 1.2 Structure of semiconductor optical amplifier

where Γ is optical confinement factor; 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. The gain coefficient (*g*) depends on the frequency *(ω)* and power of the signal (*P*) [7]. Thus, *g* is the function of *ω* and *P* and is given by equation 1.7

$$g(\omega,P) = g(\omega)/[1+ (P/ Psat)] \quad 1.7$$

This is for bulk active layer. The main reason behind the output power saturation is the reduced population inversion due to the intense input optical power that consumes the population inversion carriers. Saturation power is given by equation 1.8 [7] :

$$P_s = C\omega\hbar\frac{d\omega}{\Gamma}\frac{1}{g_d\tau} \quad 1.8$$

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, g_d is differential gain, τ is carrier lifetime and *dω/Γ* represents the mode cross-section.

On optimizing the active layer, optical confinement factor and carrier lifetime. The large saturation power can be obtained. On reducing the width of active layer result is polarization dependence. Research in this area is still in progress. The most suitable is SOA with bulk active layer to achieve large saturation power and polarization insensitive response[7-10].

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. 1.3. 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]

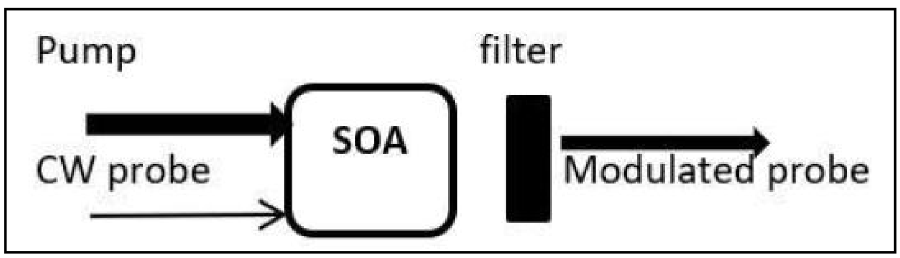
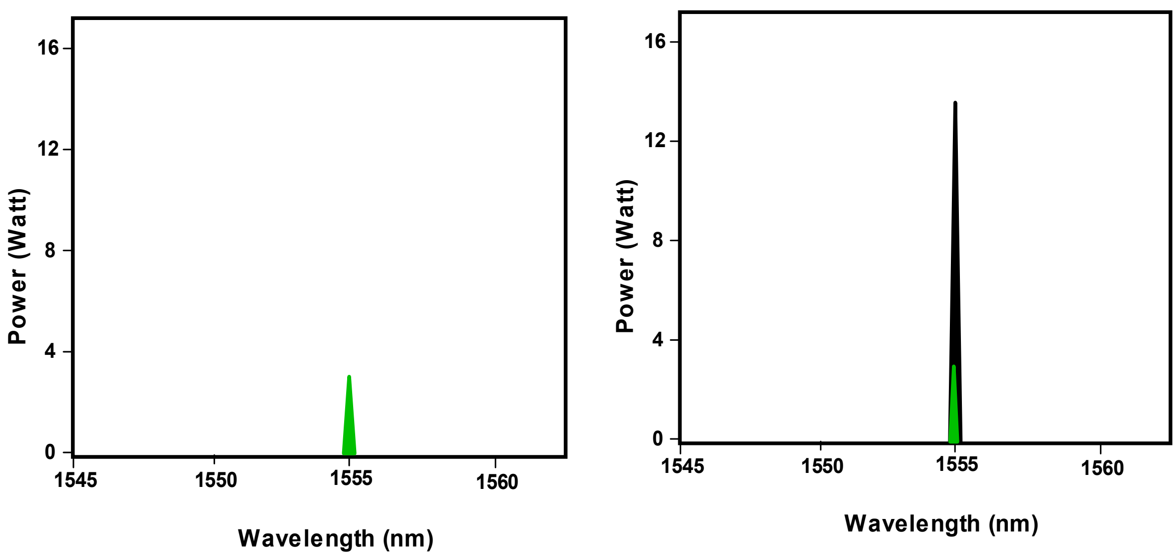


Fig. 1.3: Wavelength converter using XGM in SOA[14].



(a) (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

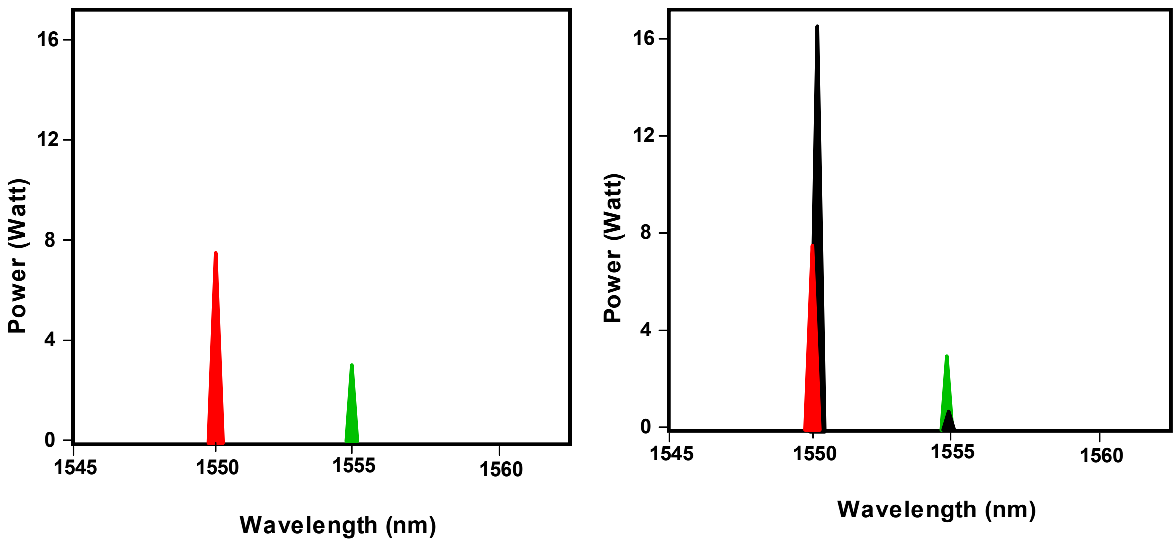


Figure 1.5(a). Effect of XGM on pump and probe pulse before passing through SOA, (b) Probe and pump after passing through SOA

The 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 1.4 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. Due to its simplicity and implementation at high bit rate, it is really attractive. The devices using XGM are insensitive to polarization[11-14].

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. Gain saturation characteristics are important in optical repeaters and multi-channel amplifiers because they require high-power operation. SPM is used to design all-optical computing devices for buffering and delaying signal pulses. Tunable all-optical delays are important for application in telecommunication, optical coherence, optical sampling etc. SPM *i.e.* each channel alters its own phase.

XPM and XGM happen when two or more signals are there. The phase and gain of each signal is modified by neighboring one.In XGM data pulse at one wavelength modulates the carrier density in SOA and at the same time results as a gain variation indentation in inverted copy of the clock pulse injected into the SOA as shown in Figure 1.3. Due to the modulation of a carrier density there is a gain compression in the pump signal that produces a chirping of the converted signal. The SOA is operated under the high optical intensity to reduce the gain recovery time. The problem related to XGM is at longer wavelength extinction ratio penalty is associated with it. This phenomena can be easily accommodated at high bit rate.

The chirp of the converted signal is used as an advantage by including the SOA in an interferometer configuration that converts this XPM into an intensity modulation. This can be done by SOA, incorporated with interferometer configuration. XPM can be used to create wavelength converters and other logic devices. XPM causes phase changes thus interferometric configuration with SOA in its arm is used 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. 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 is 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 of different wavelengths are injected into the SOA. On passing through SOA there is an intensity beating which arises due to the difference in frequency modulated signals in SOA. If the frequency separation is small the carrier density will be modulated. If the frequency separation is large, the modulated carrier will set up a moving grating in the active strip of SOA. The grating scatters the input signal and produces the sidebands which are located at the lower and higher frequency between the input signals. The power of the side bands is usually less as compared to the signal power as in Figure 1.6. The optical signals at different wavelengths merge into SOA and produce new signals at other wavelengths. 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 $(\omega - \Omega)$, 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 $\omega + \Omega$, [14].

It is a process which depends on the phase of the optical signal instead of their intensity. It is a polarization dependent phenomenon and capable of handling intensity modulation, phase modulation and frequency shift keying signal. As it depends upon distance between the signals and converted wavelengths therefore the conversion efficiency is adequately affected. Therefore the scheme is not used in all-optical network. The application of FWM is used in Dispersion management by optical phase conjugate. The process produces a mirror image of the original signal which is appositively chirped in a spectral domain[14,25].

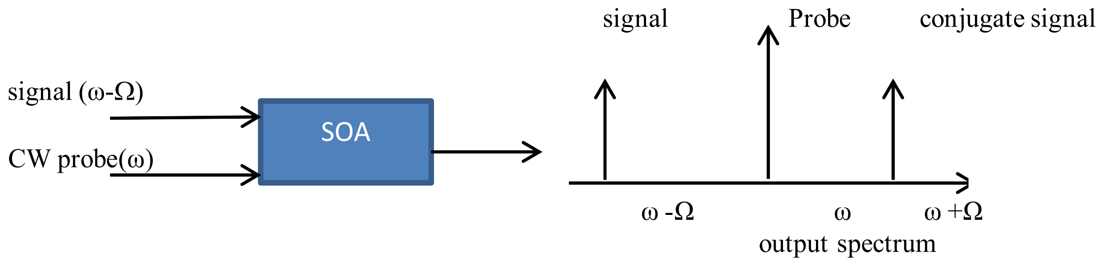


Fig. 1.6. Four wave mixing in SOA [14].

***Cross polarization modulation**:* XPolM effect occurs when a signal is injected into an SOA whose state of polarization is known. This state gets changed at output. This change in the state of polarization is a nonlinear effect. 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 Γ is different for the Transverse Electric (TE) and Transverse Magnetic (TM) Modes. This results in polarization dependence of the device gain. The birefringence is introduced due to asymmetry in waveguide that causes two propagation constants for each orthogonal TE and TM modes. The effective refractive indices will differ for the two and the typical difference is $2x10^{-2}$ [15]. The index difference of around $2x10^{-4}$ introduces a phase shift of 90^{o} between the TE and TM modes[16]. The difference in gain for the two modes can be minimized by designing a completely square waveguide[17,18].

The latest is to use in optical neural networks where all-optical neuron based on the self-induced polarization rotation in a semiconductor optical amplifier achieves reconfigurable nonlinear activation functions by tuning the initial state of polarization of input signal. {40,41} 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 and reject the slow response by using a wavelength filter[19-25] or using SOA in Mach–Zehnder Interferometer configuration with SOA in each arm i.e. SOA-MZI. It cancels out the slow response component using differential modulationand pass the ultrafast component. In both these configurations nonlinear optical effects associated with the carrier density change in SOAs are utilized.

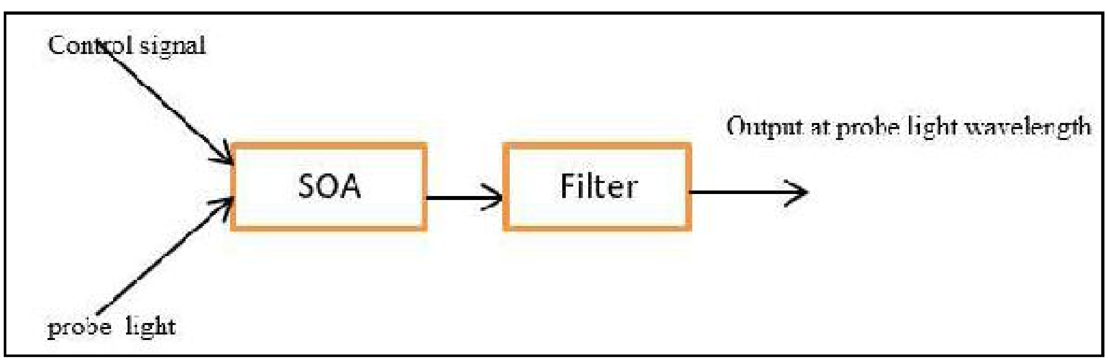
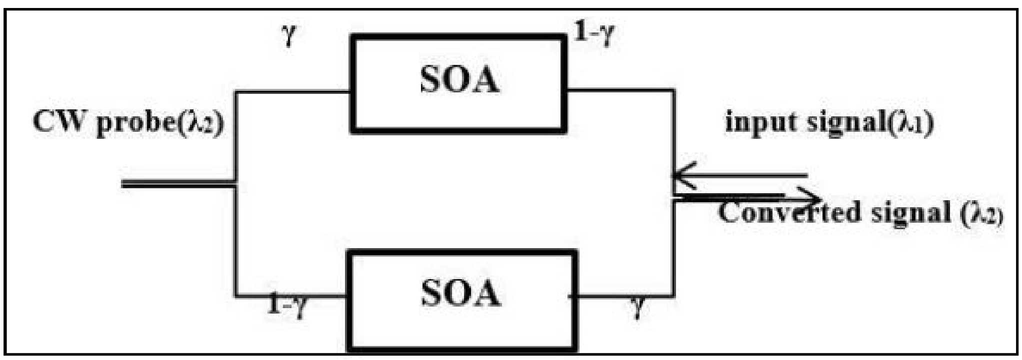


Fig. 1.7 All-optical switch based on SOA followed by an optical Band-pass filter[7].

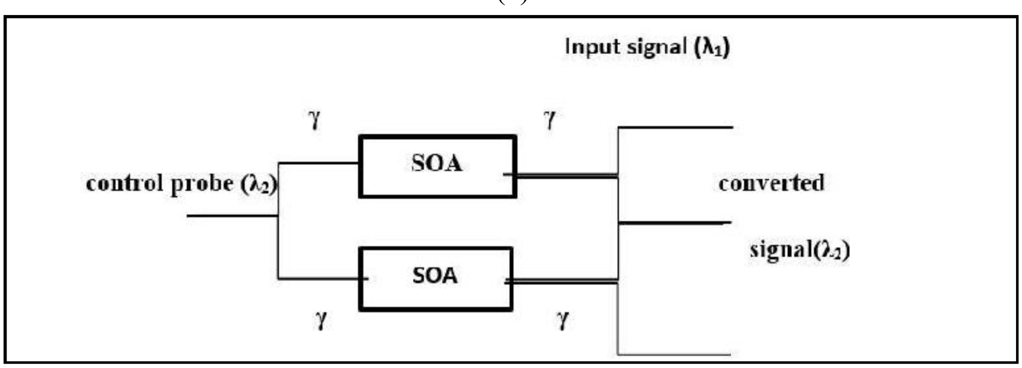
Optical filtering at the output of SOA to select only the ultrafast component is to enhance the modulation bandwidth of SOA-based optical computing devices[19-25]. The injected control signals in SOA based all-optical followed by an optical band-pass filter changes the gain and refractive index of the SOA and intensity of the co-propagating CW probe light gets modulated. The band pass filter is selected at such frequency that the probe light is transmitted and rejects the control signal.[7] Fig. 1.7 shows an all-optical switch based on a SOA followed by an optical band-pass filter.

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 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].

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 1.8 uses both the control light and the probe light. The carrier depletion is induced by control signal and gain and phase of the probe signal is modulated using XPM and XGM[29-33].



(a)



(b)

Fig. 1.8 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. 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[37] have been simulated and reported. 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. [7,23]

The dynamics of carrier density in SOAs and associated nonlinear optical effects can be analyzed by rate eqns (1.9-1.11). [7]

$$\frac{dN}{dt} = J - \frac{N}{\tau} - g_d(N - N_{tr})\frac{S_c}{\hbar\omega_c} - g_d(N - N_{tr})\frac{S_P}{\hbar\omega_P} \quad 1.9$$

$$\frac{dS_c}{dz} = \Gamma g_d(N - N_{tr})S_c - aS_c \quad 1.10$$

$$\frac{dS_p}{dz} = \Gamma g_d(N - N_{tr})S_p - aS_P \quad 1.11$$

where N is the carrier density, J is the rate of carrier injection through bias current, N_{tr} is the transparency carrier density, S_c is the control light power, S_p is the probe light power, ω_c is the control light frequency, ω_p is the probe light frequency, g_d 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. 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).

V. 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.

VI. *Scope of Future work :*

Organic materials have become popular among all optical computing devices due to high nonlinearities of third order and flexibility of molecular design, Due to the nonlinear properties of Polydiacetylenes, they can be used for switching in all-optical domain and among the most significant polymers for nonlinear optical applications. Their suitability for high-speed optoelectronics applications is due to their high response time to laser signals. Due to their high nonlinearities and flexibility of molecular design, organic materials have become popular among all optical computing devices. 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 have been used for designing all-optical logic gates. These materials are used as a photosensitive organic material in photovoltaic, photoconductive, and photo electrochemical applications. The organic compounds could be promising components for optical thin films and waveguides.

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