International Journal of Advanced Research and Development
ISSN: 2455-4030
Impact Factor: RJIF 5.24
www.advancedjournal.com
Volume 2; Issue 6; November 2017; Page No. 97-100

Nonlinear effects in semiconductor optical amplifier useful for optical computation and data processing

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Abstract
The demand for faster optical communication networks has been on the rise in the recent years. To address this demand, the new generation optical communication networks are moving towards very high data rates. Therefore, to achieve higher data rates, advance optical networks will require all optical ultra-fast signal processing. Various operations have been proposed in the field of optoelectronic computing in last three decades. Nonlinear Optical Loop Mirror (NOLM) provides a major support to optical switching based all-optical logic and algebraic processing where the switching mechanism is based on fiber Kerr nonlinearities. However, due to the weak Kerr coefficient in fibers, long fibers and high optical powers are necessary. More efficient and compact solutions can be realized by all optical switching in semiconductor optical amplifiers (SOAs) where the nonlinear coefficient is much higher. In this paper a brief review is made on different types of SOA non-linearities.

Keywords: optical data processing, non-linear optical loop mirror (NOLM), kerr non-linearity, semiconductor optical amplifier (SOA), cross gain modulation (XGM), cross phase modulation (XPM), self-phase modulation (SPM) and four wave mixing (FWM)

1. Introduction
Semiconductor optical amplifier (SOA) is a promising optical device that helps a lot in the development of network systems in communication. SOAs have attracted renewed interest for the use as basic amplifier and also as functional elements in optical communication networks and optical data processing devices. Many of these functional applications are based on SOA nonlinearities. Nonlinearities in SOA are principally caused by carrier density modulation induced by the amplifier input signals. The four main types of non-linearity are: Cross Gain Modulation (XGM), Cross Phase Modulation (XPM), Self-Phase modulation (SPM) and Four Wave Mixing (FWM).

2. Semiconductor Optical Amplifier: Its nonlinearities
2.1 Principle of Operation of SOA
The semiconductor optical amplifier (SOA) is very similar to a semiconductor laser. The first studies on SOAs were carried out around the time of invention of semiconductor laser in the 1960's. These early devices were based on GaAs homojunctions operating at low temperatures. The arrival of double heterostructure devices spurred further investigation into the use of SOAs in optical communication systems. In the 1970's Zeilder *et.al.* carried out early work on SOAs [1]. In the 1980's there were further important advances on SOA device design and modelling. Early studies concentrated on AlGaAs SOAs operating in the 830 nm range [2-4]. The fiber optic transmission systems operate in this wavelength range due to the low loss of optical fibers and the commercial application of optical amplifiers are going to be driven by their need in fiber communication systems.

Semiconductor optical amplifier has a p-cladding layer, an n-cladding layer and a gain region all of which are grown epitaxially over a binary substrate. The schematic of a semiconductor optical amplifier (SOA) is shown in Fig. 1 [5-6]. The amplifier has cleaved facets with anti-reflection coating which reduce its reflectivity to nearly zero. The amplifier has a p-n junction which is forward biased during operation. The injected current produces gain in the gain region. The majority carriers are holes in the p-cladding layer and they are electrons in the n-cladding layers. The electrons and holes are injected into the gain region which is made of a lower band gap semiconductor than the cladding layers. The co-located electrons and holes recombine. This results in spontaneous emission of light and optical gain for light

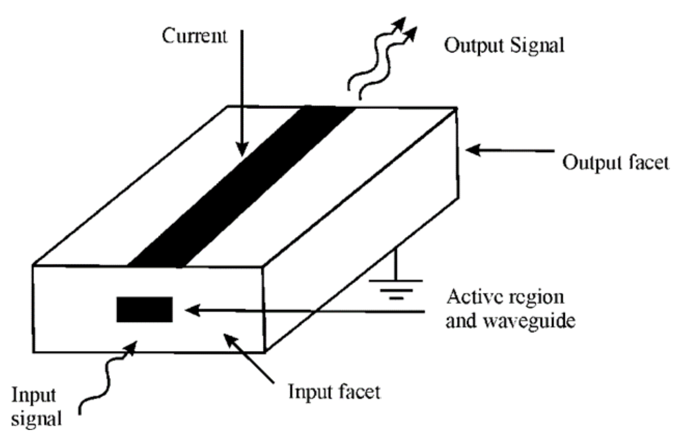

Fig 1: Schematic structure of SOA

Propagating in the gain region. It is a fortunate coincidence that semiconductors with lower band gap also have a higher index than semiconductors with higher band gap. The small index difference produces a waveguide for the propagating signal light. The signal is guided in this waveguide and it experiences amplification until it emerges from the output facet of the amplifier. Thus the double heterostructure material with n-type and p-type high band gap semiconductors around a low band gap semiconductor is instrumental in simultaneous confinement of the charge carriers (electrons and holes) and the optical signal. This is illustrated in Fig. 2. The electrons are located in the conduction band and holes are present in the valence band. In the gain region, the electrons and holes recombine to produce photons through both spontaneous and stimulated emission process. The optical gain of the input signal is due to the stimulated emission process. In the absence of current the semiconductor would absorb the incident photons. A certain minimum number density of electrons/ holes is needed to achieve net optical gain. The gain mechanism is shown in Fig. 3.

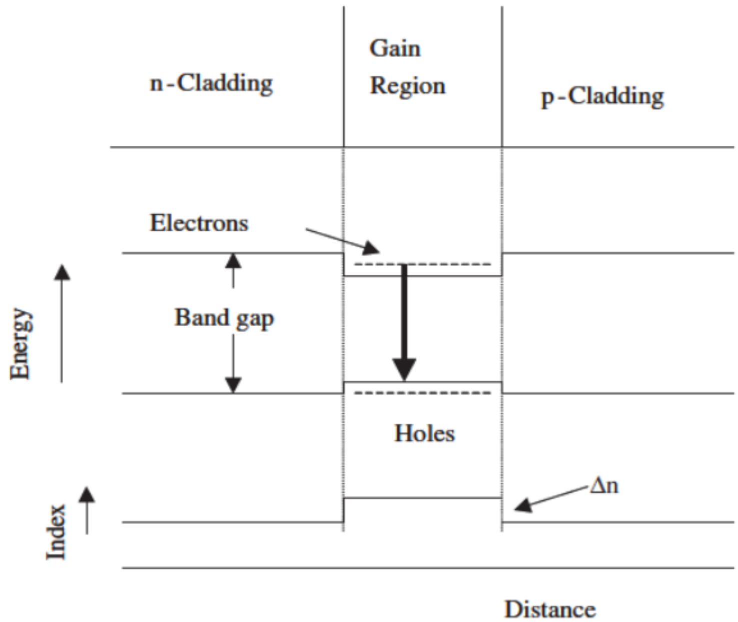

Fig 2: Schematic illustration of confinement of the electrons and holes and also Conduction band

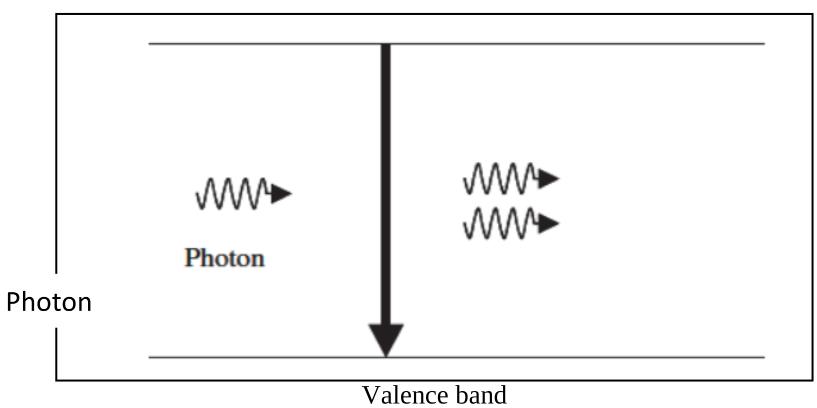

Fig 3: Schematic illustration of amplification

2.2 Cross Gain Modulation (XGM)

Cross Gain modulation (XGM) is a result of gain saturation in SOA. It occurs when light of two different wavelengths, a pump and a probe, are injected into the semiconductor optical amplifier [7-8]. When operated under gain saturation conditions, the available optical gain is distributed between the two wavelengths depending on their relative photon densities**.** The changes in the power level of the pump wavelength have an inverse effect on the gain available to the probe wavelength and result in data transfer. The most basic XGM scenario is shown in Fig. 4 where a weak CW probe light and a strong pump light, with a small-signal harmonic modulation at angular frequency are injected into an SOA. XGM in the amplifier will impose the pump modulation on the probe. This means that the amplifier is acting as a wavelength converter, i.e. transposing information at one wavelength to another signal at a different wavelength.

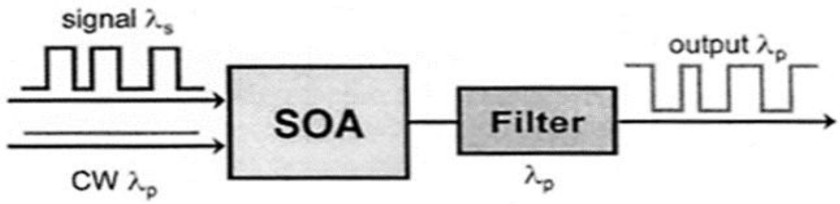

Fig 4: Cross gain Modulation scheme in SOA

2.3 Cross Phase Modulation (XPM)

A cross-phase modulation (XPM) accompanies the cross gain modulation when two optical signals are simultaneously present in the SOA [5]. An interferometer configuration can be used to convert the phase modulation to an intensity modulation. XPM in a SOA used in an interferometric configuration has been used for all-optical wavelength conversion, optical demultiplexing and for optical clock recovery. Generally a Mach-Zhender or Michelson interferometer configuration integrated on a single chip is used to convert phase modulation to intensity modulation.

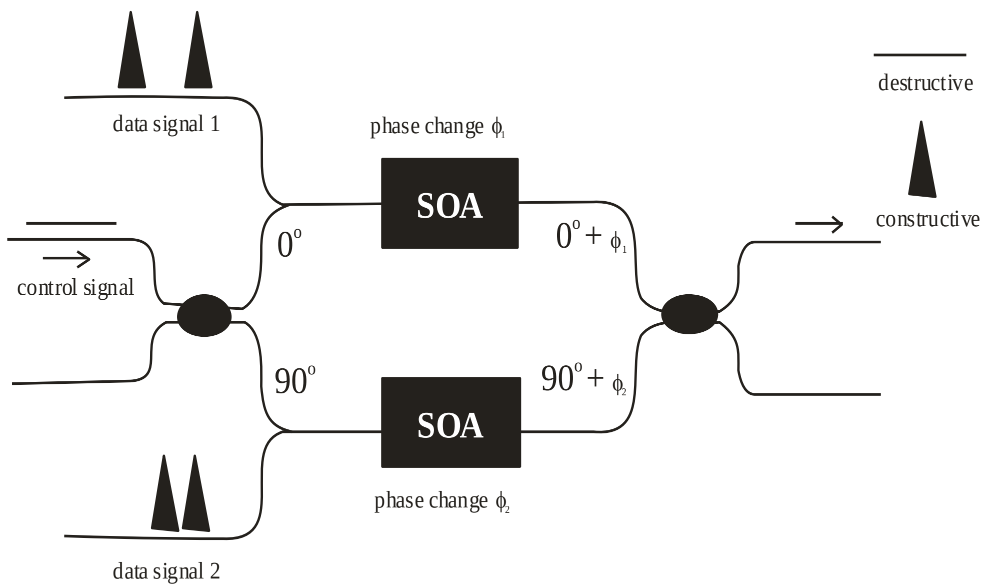

Fig 5: Cross phase modulation scheme in SOA

2.4 Self Phase Modulation (SPM)

The refractive index of an SOA active region is not constant but is dependent on the carrier density and so the material gain. This implies that the phase and gain of an optical wave propagating through the amplifier are coupled via gain saturation. This self-phase modulation (SPM) will change the pulse shape as well as its spectrum. This effect can be used to create a dispersion compensator where SPM pulse narrowing is used to compensate for pulse broadening resulting from chromatic dispersion in optical fibre. This type of device has great potential for increasing the capacity of high-speed long-haul fibre links. If more than one signal is injected into an 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 some form of interferometric configuration to convert phase changes in the signals to intensity changes using constructive or destructive interference.

2.5 Four Wave Mixing (FWM)

Four-wave mixing (FWM) is a coherent nonlinear process that can occur in an SOA between two optical fields, a strong pump at angular frequency and a weaker signal (or probe) at having the same polarization [6-8]. The injected fields cause the amplifier gain to be modulated at the beat frequency. This gain modulation in turn gives rise to a new field at as shown in Fig. 7. The new field is called the conjugate because its phase is the opposite of the signal phase. This means that the spectrum of the conjugate signal is a shifted and inverted replica of the input signal. FWM generated in SOAs can be used in a many applications including wavelength converters, dispersion compensators and optical demultiplexers. FWM in SOAs arises from different physical phenomena. At low the dominant mechanism is modulation of the carrier density resulting from pump-signal beating. This is an interband effect as it involves carrier-hole recombination between the material conduction and valence bands. Because of this the characteristic time of this process is the carrier lifetime.

This is the order of hundreds of picoseconds. This implies that this particular mechanism will only manifest itself for detuning frequencies of the order of tens of GHz.

Four-wave mixing (FWM) is a process by which optical signals at different (but closely spaced) wavelengths mix to produce new signals at other wavelengths, but with lower power. In the FWM process, light at two frequencies, f_1 and f_2, are injected into the amplifier. These injected signals are generally referred to as pump and probe beams. The pump and probe beams can be obtained from two single wavelength distributed feedback (DFB) lasers. The pump signal is of higher power than the probe signal. Consider the case when both the pump and the probe signals are CW. Propagation through the SOA results in the generation of two additional FWM signals with frequencies $2f_1 - f_2$ and $2f_2 - f_1$. The intensity of light at these wavelengths is measured using a spectrometer. The FWM signal at frequency $2f_1 - f_2$ has higher power if the pump signal strength (at frequency f_1) is higher than that of the probe signal. If I_1 and I_2 are the intensities of the signals at frequencies f_1 and f_2, the intensities of the signals at frequencies $2f_1 - f_2$ and $2f_2 - f_1$ are proportional to $I_1^2 I_2$ and $I_1 I_2^2$ respectively. The scheme of FWM is shown in Fig. 6.

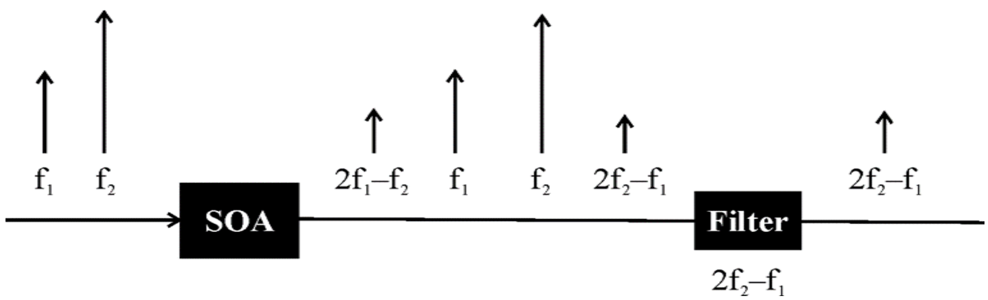

Fig 6: Wavelength conversion based on FWM in SOA

3. Conclusions

In this paper principle of operation of SOA and its non-linear behavior is described is described. The different types of non-linearity may lead to different switching mechanism. There is a enough scope of modeling of SOA non-linearity assisted switching mechanism. detail theoretical investigation.

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