“ALL OPTICAL WAVELENGTH REGENERATION BY SOA’s IN A MACH ZEHNDER CONFIGURATION”

A Dissertation Submitted towards the Partial Fulfillment of

the Award of Degree of

MASTER OF TECHNOLOGY

IN

MICROWAVE AND OPTICAL COMMUNICATION ENGINEERING

BY

GOPAL

ROLL NO. 02/MOC/2010

DEPARTMENT OF

ELECTRONICS & COMMUNICATION ENGINEERING

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UNDER THE GUIDANCE OF

Prof. R. K. Sinha

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CERTIFICATE

This is to certify that the dissertation titled ***"All Optical Wavelength Regeneration by SOA's in a Machzehnder Configuration"*** is the authentic work of **Mr. Gopal** under my guidance and supervision in the fulfillment of requirement towards the degree of Master of Technology in Microwave and Optical Communication Engineering , jointly under the Deptt of Electronics and communication engineering and Deptt. Of Applied physics of Delhi Technological University. The contents of this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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LIST OF SYMBOLS

λ	Wavelength
λ_p	Pump wavelength
λ_s	Signal wavelength
AOWC	All optical wavelength converters / conversion
ARC	Anti-reflection coating
ASE	Amplified spontaneous emission noise
BER	Bit error rate
BW	Bandwidth
CD	Chromatic dispersion
CLK	Clock
CW	Continuous wave
DC	Direct current
DEMUX	Demultiplexer
DFB	Distributed feedback
DH	Double heterostructure
DWDM	Dense wavelength division multiplexing
EDFA	Erbium doped fiber amplifier
EOP	Eye opening penalty
ER	Extinction ratio
F	Contrast factor
F_r	Minimum resolvable bandwidth
FP	Fabry Perot
FPF	Fabry-Perot filter
FSR	Free Spectral Range
FWHM	Full-width at half maximum
FWM	Four-wave mixing
HNLF	Highly non-linear fiber
IL	Insertion loss
MZ	MachZehnder
MZI-SOA	MachZehnder interferometer with semiconductor optical amplifiers
MZM	MachZehnder Modulator

OCDMA	Optical code division multiple access
OEO	Optical-electro-optical
OEWC	Optoelectronic wavelength conversion
OF	Optical filter
OOK	On-off-keying
OTDM	Optical time division multiplexing
PMD	Polarization mode dispersion
PON	Passive optical network
PRBS	Pseudo-random bit sequence
r_{ij}	Reflection coefficient
R	Reflectivity of mirror
RZ	Return-to-zero
SL	Semiconductor laser
SLA	Semiconductor laser amplifiers
SLED	Superluminescent Light Emitting Diodes
SLPM	Spatial light phase modulator
SOA	Semiconductor optical amplifier
SPM	Self-phase modulation
SSB	Single sideband
TDM	Time division multiplexing
WC	Wavelength converters / wavelength conversion
WDM	Wavelength division multiplexing
XGM	Cross gain modulation
XPM	Cross phase modulation
XPR	Cross polarization rotation
1R	Regeneration: reamplification
2R	Regeneration: reamplification and reshaping
3R	Regeneration: reamplification, reshaping, and retiming

ABSTRACT

In this project, All-optical Wavelength regeneration using SOA in machzehnder configuration is investigated. These processes may find a variety of applications in future high-capacity fiber-optic transmission systems including low-noise amplification. With the outcome of the EDFA and dispersion compensation techniques, transmission of optical signals over hundreds or thousands of kilometers became possible without intermediate OEO regenerators. The increasing demand for optical bandwidth has lead to the development of WDM systems and to the increase of the per channel bit rate. In parallel to the explosion of per channel bit rates and transmission distances, optical systems are also evolving from simple transmission systems to a higher level of complexity, where switching and signal processing is supported by the optical layer. By eliminating the *electronic bottleneck*, all-optical signal transmission and processing are expected to enable the next generation of optical networks, by dramatically reducing costs, energy consumption, and increasing the network throughput. The increase of the per-channel bit rate usually leads to a reduction of the signal tolerance to optical impairments. Such optical impairments are mostly originated from propagation and from signal processing. Propagation degrades the optical signal due to various distortion sources; such as: uncompensated chromatic dispersion, polarization mode dispersion, non-linear effects, or noise accumulation. Optical signal processing degrades the signals by tight optical filtering; crosstalk in photonic-cross connects; polarization dependent losses (PDL) of components; and by imperfect optical functionalities, like wavelength or format conversion.

Signal degradation in optical systems is typically overcome by adding regeneration stages at periodic transmission distance intervals. The most common type of regeneration consists in detecting the optical signal, recovering it in the electrical domain and retransmitting it. However, this technique suffers from the general disadvantages of OEO signal processing. On the other hand, all-optical regenerators are expected to overcome the drawbacks of OEO converters and are considered essential elements for fully-functional optical networks; however, all-optical regeneration at high bit rates is still a research topic.
Regeneration can be divided in the three main functionalities: re-amplification, re-shaping, and re-timing. The simplest functionality is *re-amplification* (or 1R), which consists in

simple optical amplification. A device which also provides *reshaping* in addition to *re-amplification* is known as 2R. *Re-shaping* consists in increasing the contrast between the two logical levels; which improves the required optical signal to noise ratio (OSNR) for a specific bit error rate (BER) level. Finally, 2R is combined with *re-timing*, to create a full 3R. Re-timing refers to the reduction of the signal jitter.

Chapter 1

Introduction

In optical communications, the laser light is mainly used to carry information from source to destination. The optical carrier frequency of the order of few THz can allow fast data modulation rates up to hundreds of GHz. Because of the increase in the number of user, call subscriber, increase in the demand of internet, Facebook, Google, hence the data requirement is high. Therefore in recent years, a great interest has been developed in optical communication field, after the growth in the technologies of lasers, optical fibers, and semiconductor waveguides. Clock recovery and data regeneration are essential operations in optical digital communications. Clock recovery is one of the most important tasks at network nodes and receivers as it allows synchronous signal processing operations, which usually yield a high performance. Optical transmissions suffer from optical impairments. Transmission of data along optical fibers for long distances result in data degradation and distortion, due to the optical fiber impairments such as Kerr nonlinearities and chromatic dispersion, in addition to accumulated noise through cascaded optical amplifier stages. Therefore, the use of optical signal repeaters and regenerators at periodic transmission distances is desirable to re-amplify, re-shape, and re-time the transmitted data bits. This way longer transmission distances can be reached with an error free operation.

Currently deployed systems of signal processing use optical-electrical-optical (O-E-O) technology. In this approach, the received optical data is detected and converted into an electrical signal for electronic processing. The processed data is then converted into optical signal using electrical/optical converters in order to retransmit along optical fiber. This conversion process is limited by the speed of electronic components, which represents a bottleneck for high-speed optical processing that supposed to function at high data rates up to 160 Gbit/s or beyond. In order to overcome this bottleneck and make use of the high-speed and the wide bandwidth available in optical fiber systems, optical-regeneration technology can potentially work with lower power consumption and much more compact size and can provide transparency to protocol and the formats. Optical regeneration generally includes 3R: retiming, reshaping and re-amplifying. Some optical regeneration techniques are 2R, excluding retiming. .

The main objective of this thesis is to contribute to the study and development of all-optical regeneration using semiconductor optical amplifier in machzehnder configuration, concentrating on some of the requirements of commercial systems: low cost, simplicity and robustness.

1.1 Motivation

The functionalities required from an optical network are increasing rapidly. Years ago it was sufficient that an optical system would transmit high volumes of information over large distances. Nowadays, it is also required that the optical network performs signal processing over the information being transported.

Optical networks are now a mixture of dense wavelength division multiplexing, and optical time wavelengths are combined in the same optical fiber with outstanding spectral efficiency. OTDM consists in interleaving several incoming signals in the same wavelength, reaching ultra-high per-channel bit rates. Currently, all this information is processed in the electrical domain to achieve the required functionalities, which consist mostly in:

Wavelength conversion: where an input signal at wavelength λ_1 is converted to λ_2. Wavelength converters are key devices to increase network throughput and avoid wavelength blocking.

Regeneration: optical signals are distorted by several impairments in fiber transmission (such as dispersion, nonlinearities, polarization mode dispersion (PMD), noise from amplification) and in the switching nodes (tight filtering, crosstalk, etc.). Regeneration consists in converting a distorted signal in an undistorted one Performing such operations in the electrical domain generally leads to a *bottleneck effect*, since the optical transmission capacity and costs keep improving but the processing capabilities are limited by slower, more expensive and in general less efficient electronics.

All-optical functionalities are usually achieved by exploiting the non-linear characteristics of optical mediums. Most research has focused on optical fiber, (mostly highly non-linear fibers [1]) and semiconductor optical amplifiers (SOA) [2] as nonlinear mediums. In fiber, the interaction between the signals and the medium is called non-resonant and has an ultrafast response time (in the order of the femto-seconds); however, the efficiency is usually low, since the non-linear coefficients are relatively low.

As a consequence high input optical power or large interaction lengths (hundreds of meters) are commonly required to achieve reasonable non-linearity. On the other hand, SOA have a much higher non-linear coefficient, but the temporal response of its nonlinear applications is limited to tens or hundreds of picoseconds by slow carrier dynamics. Nevertheless, ultra-fast SOA operation is being enabled using, for example, a Machzehnder Interferometer structure with SOA in each arm (MZI-SOA), operated in a differential mode. SOA have also the advantage of being integrable, have potential for low cost, provide optical gain, are stable, and can be operated with very simple schemes.

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1.2 Thesis objective and outline

The objective of this thesis is to contribute for the development of all-optical regeneration and conversion, which may constitute the building blocks for the all-optical routers of the future. We focus on surpassing the SOA inherent limitations, such as slow response time or signal degradation due to intra-channel distortion, and on developing some of the urgent network requirements, such as wavelength converters and regenerators.

This thesis is organized in five chapters where several SOA based functionalities are investigated, the introduction chapter, and a conclusion chapter.

Chapter 2 describes an overview of the history behind SOA developments. An overview of the principle behind amplification in semiconductor materials is shown, and techniques employed for the design of more efficient SOA are also given. The non-linear behavior of SOA is detailed regarding gain and phase dynamics. Such dynamics are the base of all applications studied throughout this work. The simulation model considered in the rest of this work is presented. This chapter also includes several applications of SOA.

Chapter 3 is focused in wavelength conversion. This is most basic all-optical functionality and the principles behind it are fundamental for the development of other processing functionalities. Wavelength converters are divided in four main groups, depending on the main non-linear effect involved: cross-phase modulation (XPM), crossgain modulation (XGM), cross-polarization rotation (XPR), and four-wave mixing (FWM).

Chapter 4 is focused on a brief historical perspective of the works of Fabry and Perot that contributed to the discovery of the Fabry-Perot filter. The basic parameters and figures of merit that are important for the design of this component are given. The chapter will conclude with a discussion of various sources of loss in Fabry-Perot filters and the effects of these losses on performance.

In **chapter 5,** Optical regeneration is studied. Propagation degrades the optical signal due to various distortion sources; such as: uncompensated chromatic dispersion, polarization mode dispersion, non-linear effects, or noise accumulation. All-optical regenerators are expected to overcome the drawbacks of OEO converters and are considered essential elements for fully-functional optical networks. Then, we have described some regeneration techniques and clock recovery is shown.

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Chapter 6 delivers conclusions and Proposals for future work are also presented

Chapter 2

Semiconductor optical amplifiers

Semiconductor optical amplifiers (SOA) are the key device for the all-optical processing functionalities studied and proposed in this thesis. This chapter presents an overview of the history behind the development of SOA and of some basic design principles to optimize its characteristics. Propagation of optical signals in SOA is analyzed via gain and phase dynamics. The simulation model utilized throughout this work is detailed, which includes intra and interband effects. Finally, the most relevant linear and non-linear applications of SOA are presented.

2.1 Historical development

The development of semiconductor optical amplifiers (SOA) is closely related to progresses in semiconductor lasers (SL) technology. The first SOA were regular laser diodes biased below threshold [2]: SOA are also known as semiconductor laser amplifiers (SLA) in the early literature [3], [4], [5]. In 1966, anti-reflection coatings (ARC) were proposed to reduce the optical feedback and allow amplification of infrared light [6]. The double hetero-structure was demonstrated in 1969 and led to significant improvements in both lasers and SOA, such as enabling operation at room temperature. Whilst first studies focused AlGaAs SOA, operating in the 830 nm range [7], in the 80's decade InP/InGaAsP SOA were designed for operation in the 1300 nm and 1550 nm ranges [3].

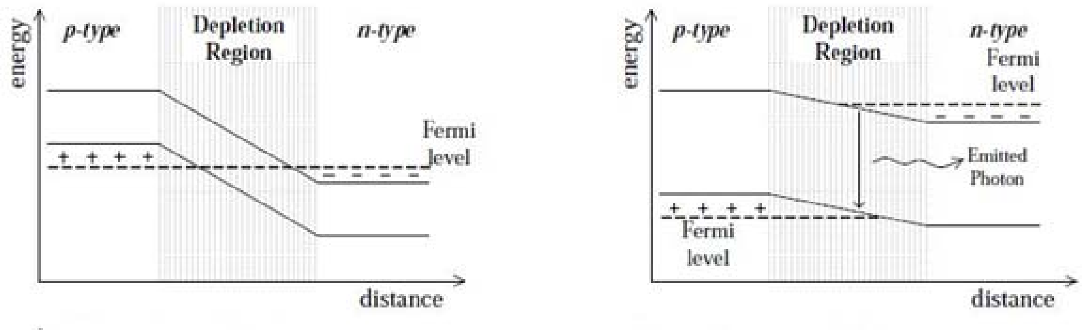
By the second half of the 80's the first transmission tests employing SOA as in-line amplifiers were reported; however, in 1987 the Erbium doped fiber amplifier (EDFA) was invented [4] and began to compete with SOA for linear amplification purposes. The first true travelling wave SOA (TW-SOA) is reported in the end of the 80's [4]. These devices are enabled by developments in anti-reflection coatings and feature low polarization sensitivity – one of the main drawbacks of early SOA. By mid 90's the first semiconductor amplifiers featuring simultaneously high gain, high saturation power, and low polarization dependence are reported. More recently, quantum-dot SOA (QDSOA) have been developed to provide higher cross signal independence, lower biasing currents and wider operation bandwidths, along with other advantages. Currently, SOA are presented as enabling devices for low cost amplification and processing in access networks, since these can be used in photonic integrated circuits [27], allowing integration with several other optical components – passive or active. Moreover, SOA are compact, electrically pumped, have a large optical bandwidth, and allow flexibility in the choice of the peak gain wavelength. Due to their non-linear characteristics and fast response, SOA are also key devices for state-of-the-art all-optical processing at ultra-high bit rates (BR).

The increase in the per channel bit rate and in the total number of wavelength multiplexed channels are exhausting the electrical processing capabilities of networks. Electrical processing at ultra high bit rates, such as 40 Gb/s and superior has high costs, footprint and energy consumption. As a consequence, all-optical regeneration is currently one of the key research topics in optical networks.

2.2 Principle of SOA operation

The operation of semiconductor optical amplifiers requires bringing together a p-type semiconductor and an n-type semiconductor to form a p-n junction. The denominations n- and p-type refer to the semiconductor doping with impurities that have an excess valence electron or one less valence electron, respectively, when compared to the semiconductor atoms [8]. Figure 2-1 depicts the energy band of a p-n junction. In thermal equilibrium, the Fermi level1 must be continuous across the junction (also known as depletion region). Under such condition, the charged particles set an electrical field that prevents diffusion of electron and holes across the depletion region (Figure 2-1 a)). By applying an external electrical voltage, the built-in electrical field is reduced, resulting in diffusion of electrons and holes across the depletion region. When an electron and a hole are present in the same region, recombination can occur, and a photon is produced.

A photon may be generated through stimulated or spontaneous emission. *Spontaneous emission* originates photons with random phase and frequency; these are essentially noise and contribute to reduce the optical gain. On the other hand, *stimulated emission* is the mechanism responsible for the optical gain: the newly generated photon is identical to an emitting photon. Besides the radiative mechanisms, referred before, in a semiconductor material electrons and holes can also recombine non-radiatively. These recombinations are not beneficial to the amplifier operation, thus efforts are made to its minimization.



(a) Thermal Equilibrium; (b) Under Forward Bias.

Figure 2-1: Energy band diagram of a homostructure p-n junction [8].

2.3 Design of SOA

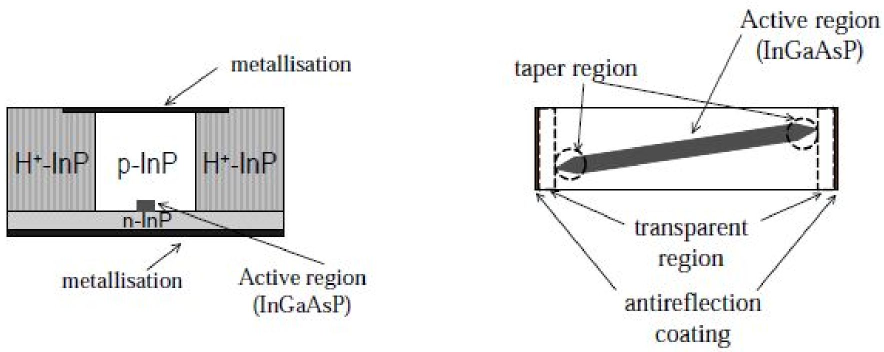
Since the development of the first SOA devices, efforts have been made to improve their characteristics [2] for application in optical networks. Ideally, an optical amplifier should feature the following characteristics

- High gain, bandwidth, and saturation power;
- Negligible reflections at the end facets;
- Efficient coupling at the input and output;
- Polarization independent amplification;
- Low spontaneous emission noise;
- Low bias current sensitivity; and low temperature dependence.

To meet such requirements, it is required to optimize the SOA design. The SOA structure is usually a double heterostructure [8], where the active layer is sandwiched between layers with different band gap energies. This configuration enables better confinement of the carriers to the active region, improving the device efficiency. Undesired reflections can be minimized through the simultaneous use of several methods, which have enabled reflectivities lower than 10^{-5}:

- Use of antireflection coating (ARC) at the end facets of the device [11];
- Utilizing angled facet structure, where the active region is not perpendicular to the facet cleavage plane;

- Guard a transparent region between the active layer and the active region end facets: window-facet structure.



a) Cross section; *b) Top view with angled facet structure.*

Figure 2-2: Schematic representation of a buried ridge stripe SOA.

Polarization independence is usually achieved by the use of a waveguide with a square cross section (and taper region to improve coupling efficiency). Other techniques can also be employed to enable polarization independence: ridge-waveguide SOA and structures based on strained materials. In Figure 2-2 a schematic representation of a buried ridge stripe SOA is depicted, showing some of the design techniques referred before. Semiconductor optical amplifiers are often classified in two main types depending on the facet reflectivity [5]: Fabry Perot (FP) amplifiers and travelling wave amplifiers (TW). A FP-SOA is a resonant amplifier while TW-SOA features reduced facet reflectivity. Due to their characteristics, TW-SOA has replaced FP-SOA in most applications. Consequently, TW-SOA will be simply referred as SOA hereafter.

2.4 Materials and structures for the active layer

The type of material and the structure of the active region determine the behavior of the SOA regarding unsaturated gain, gain spectral bandwidth, central wavelength, polarization dependence, etc. The most common structures are: bulk, and quantum well [8]. In a *bulk* material all the dimensions of the active layer are significantly larger than the deBroglie wavelength, and the energy levels of the electrons and holes in the active region are continuum [8]. In *quantum well* (QW) materials, the active region has one or more dimensions (usually thickness) of the order of magnitude of the deBroglie wavelength. Single QW devices have low carrier and optical confinement and high polarization dependence; therefore, are not commonly employed. Such drawbacks are avoided by the use of multi-QW (MQW). MQW materials have a series of stacked thin active layers separated by thin barrier layers [10]. MQW devices have discrete energy density levels; therefore, the dependence with the photon energy (thus, its frequency) decreases: larger gain bandwidth is achieved [10]. MQW also present improved noise figure, higher optical gain, and higher saturation power [2]. On the other hand, bulk devices may be more interesting to non-linear applications, since these usually feature large optical confinement and phase to amplitude coupling. SOA employing quantum dot materials are (QD SOA) currently blooming and being intensively studied. The active layer consists on nano-size semiconductor islands spatially isolated, which exchange carriers with a wetting layer; therefore, the energy states in the active layer are discrete. QD-SOA are still under research, but it is expected that when mature they will present the following characteristics [12]:

- Ultrafast gain recovery (order of the picoseconds);
- Low noise figure;
- Broadband gain;
- High saturation output power;
- High four wave mixing efficiency;
- Low threshold current;
- Low patterning effects;
- Multi wavelength conversion;
- Possibility of efficient 3R.

2.5 Gain and phase dynamics in SOA

Ideally an ideal amplifier should feature constant gain, regardless of the input power. However, the gain of amplifiers saturates for high power input signals, resulting in different gain for input signals with different power values. This effect is usually called gain saturation and is represented in Figure 2-3. For low input / output powers, the amplifier delivers a high gain, usually know as *small signal gain*; as the power increases the gain is reduced. The output power at which the gain is 3 dB bellow the small signal gain, is known as *saturation output power*.

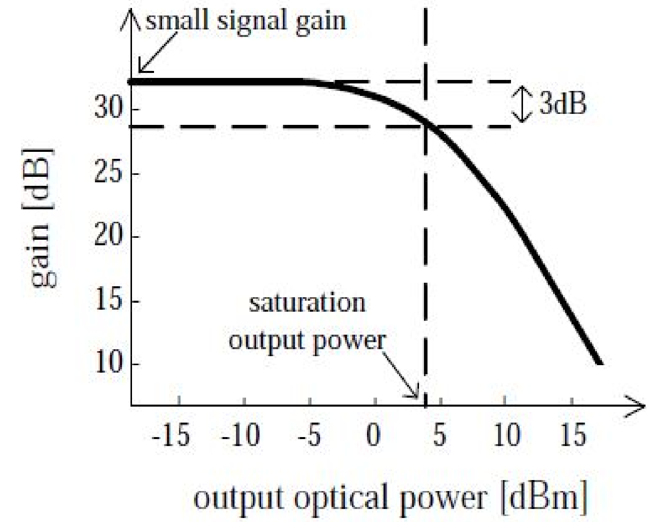


Figure 2-3: Representation of gain saturation in an optical amplifier.

In an EDFA, the gain dynamics are in the order of the milliseconds, while optical signals usually have bit periods in the order of the picoseconds. As a consequence, gain saturation occurs due to the average power of the signal being amplified, resulting in negligible inter- and intra-channel distortion. In SOA, the gain dynamics are reasonably fast: in the order of the tens of picoseconds, which is a value comparable to the pulse duration in current systems. The SOA gain saturation provokes intra and inter-channel patterning effects and newly generated frequencies, i.e. four-wave mixing (FWM). Moreover, phase modulation also occurs in the SOA due to variations of the refractive index with the input power. From the later considerations, it is evident that if a SOA is to be used as a linear amplifier, the input signal power must be carefully chosen to prevent undesired distortion effects. On the other hand, the fast gain and phase dynamics can be exploited for non-linear applications. The gain and phase dynamics of SOA are associated to the dynamics of free carriers. The free carriers density and distribution vary due to intra-band and inter-band transitions which are represented schematically in Figure 2-4. In inter-band transitions, carriers transfer from the conduction band to the valence band and vice versa. These transitions are determined by electrical pumping, stimulated and spontaneous emission, non-radiative recombination, and two photons absorption (TPA) [2]. In intra-band transitions, the energy distribution of the carriers varies within the same band and is determined by: spectral hole burning (SHB), free carrier absorption (FCA), carrier heating (CH), and carrier cooling (CC) [2].

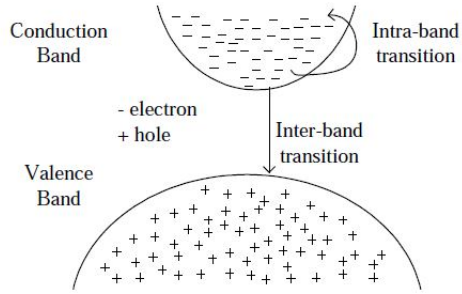


Figure 2-4: Representation of intra-band and inter-band transitions in a semiconductor.

The carrier dynamics are evident through the gain response to an ultra-short optical pulse, as represented in Figure 2-5. The incoming optical pulse stimulates carriers which have energies similar to the incoming pulse photon to recombine. This provokes a hole in the carrier distribution and is associated with SHB. The carrier density within the band is also reduced via stimulated emission. Simultaneously, TPA occurs since there is a high photon density in the active region. FCA also takes place: a free carrier absorbs a photon and moves to a higher energy level in the same band. Carrier depletion is a fast process.

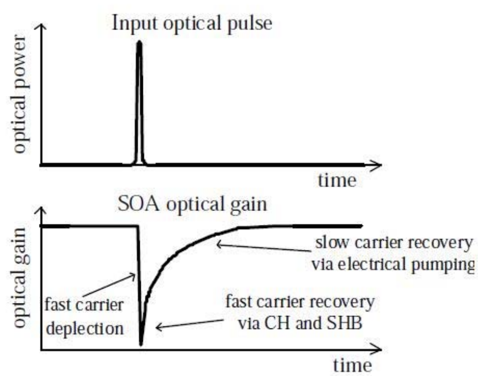


Figure 2-5: Representation of the SOA gain response to an optical pulse and associated carrier dynamics.

When the optical pulse leaves the SOA, the Fermi distribution is restored through carrier-carrier scattering; the related time constant is referred as SHB relaxation time. Although the Fermi distribution is restored, the carrier temperature has been increased due to stimulated emission, FCA and TPA. The temperature decreases via phonon emission; the related time constant is referred as CH or temperature relaxation time. These are fast intra-band processes. The original carrier level is then restored by means of electrical pumping, which is a slow process (hundreds of picoseconds). More information on carrier dynamics can be found in [2].

2.6 Applications of SOA

In the last decades SOA have been proposed not only as low cost amplifiers, but also as a promising core component for the all-optical networks of the future. An overview of the main applications of SOA is presented in this section.

Linear Amplifier

SOA have low cost potential due to: compatibility with monolithic integration [9], being electrically pumped, and allowing flexibility in the selection of the peak gain wavelength. Therefore, these devices have been pointed as an interesting solution to perform linear amplification, particularly in access and metropolitan networks, where the amplification performance requirements are not so strict [13]. Figure 2-6 illustrates a WDM network employing SOA as booster, in-line amplifier, and pre-amplifier variants.

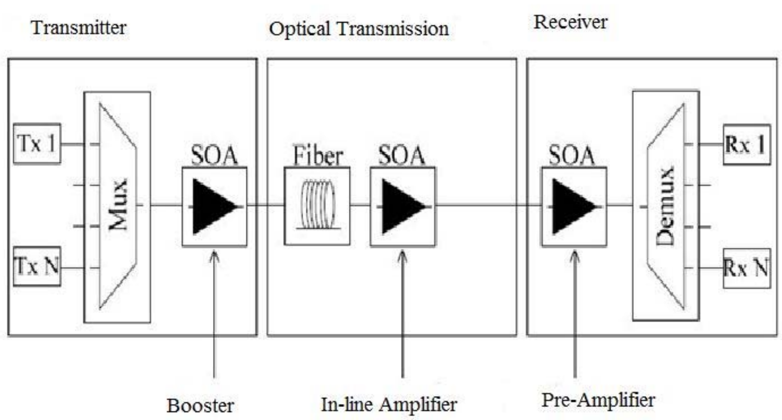


Figure 2-6: Application of SOA as linear amplifier in booster, in-line and preamplifier variants.

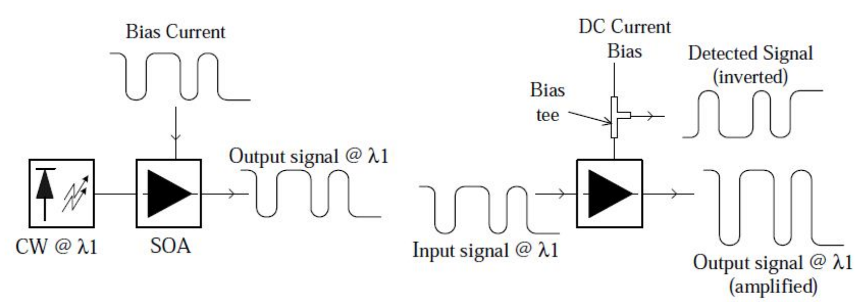
Experimental SOA based transmission tests have demonstrated 10 Gb/s single channel transmission over 550 km of standard single mode fiber, at 1300 nm . Tests with WDM signals demonstrated transmission over 1050 km of eight 10 Gb/s channels at 1550 nm, and 640 km of sixteen 10 Gb/s channels. In analogue transmission systems, such as CATV, the linearity requirements are more stringent than in the digital systems referred above;

therefore, special SOA have been developed: gain-clamped SOA, which have been described in the previous section. One of the main impairments to the use of SOA as linear amplifiers is the degradation of signals with advanced modulation formats, which carry phase information, due to cross-phase modulation at the SOA. However, in [14] we have demonstrated amplification of optical single sideband (OSSB) signals, whose sideband suppression relies on phase modulation, with reduced sideband suppression penalty, provided that the input power is controlled.

Optical modulator and detector

SOA have been proposed as optical modulator and receiver, with particular interest in low bit rate access networks. SOA are particularly interesting since they perform the referred applications and simultaneously amplify the signal. These applications are shown in Figure 2-7.

The principle of operation of an intensity modulator based on SOA is quite simple: the power of the output amplified signal is dependent on the bias current; therefore, optical modulation is performed by modulating the bias current with the information to be transmitted. This is a low price modulator with reduced complexity; it provides gain; and also features polarization and wavelength independent operation (if the SOA is polarization insensitive and the input signal is within the gain bandwidth of the SOA). When an IM signal is being amplified in a SOA, the carrier density is modulated with the inverse of the logical information of the input signal. The carrier density variations lead to a modulation of the junction voltage, resulting in a detection process. The main disadvantage of SOA being used as modulators and detectors is that the operation is typically limited by the inter-band recombination to few GHz. ME-SOA are also promising devices for detection and modulation, as discussed in section 2.4.2.



(a) Modulator *(b) Detector*

Figure 2-7: Application of SOA as modulator and detector

Wavelength Conversion

Wavelength converters (WC) are key elements in all-optical networks. SOA based wavelength converters usually use one of the following non-linear effects: cross gain modulation (XGM), cross phase modulation (XPM), cross polarization rotation (XPR), or four wave mixing (FWM). All-optical wavelength converters (AOWC) based on SOA are studied in Chapter 3.

Logic gates

Ultra fast logic operations are fundamental for the inline processing capabilities of next generation networks. Most of the network related functionalities such as add–drop multiplexing, packet synchronization, clock recovery, address recognition, and signal regeneration require logical operations, which should be performed all-optically, especially for high data rates. Several implementations of all optical logic functionalities using SOA have been presented, from the following are highlighted: XNOR, AND, NOR, and NOT functionalities achieved using a simple scheme which employs a single SOA and optical filtering [15]; several simple and complex logic functionalities are achieved via FWM in SOA for polarization shifted keying modulated signals in [78]; parallel MZI-SOA also can provide multiple logical functionalities, like XOR, NOR, OR, and AND, reported in [15].

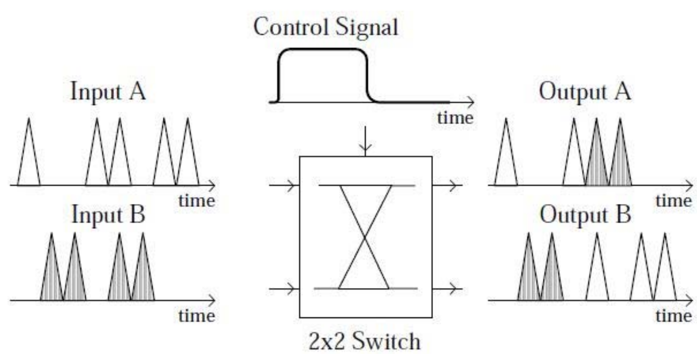


Figure 2-8: Operation of a 2x2 space switch [15].

All-optical routing also requires effective 2x2 space switches. Figure 2-8 demonstrates the operation of a 2x2 space switch: inputs A and B are switched either to output A or B, depending on the logic state of the control signal. 2x2 space switches can be implemented using MZI-SOA with 4 input ports [15]. Due to the difficulty in obtaining an exact π phase shift between the two arms and gain compression, the MZI-SOA has an inherent imperfect contrast ratio of the output ports: the input signals are not completely switched between the two output ports. Nevertheless, over 20 dB extinction ratio between the two ports are reported in [15], by independently controlling the SOA bias currents and phase shifters of the two arms.

Multiplexing and add-drop multiplexing

Future networks are likely to simultaneously employ WDM and optical time division multiplexing (OTDM). In the later, the lower bit rate information of several users is bit interleaved to generate a higher bit rate signal. To allow dynamic switching and routing it is essential to develop all optical demultiplexers and add-drop multiplexers. Demultiplexing and add-drop multiplexing is illustrated in Figure 2-9. In a demultiplexer one of the bit interleaved channels is extracted from the higher bit rate data stream. The pulse train should be at the base data rate and in phase with the channel to extract. In an add-drop multiplexer one (or more) channel is extracted (*drop channel*) and is replaced by a new channel (*add channel*). The most promising results for demultiplexers and add-drop multiplexers are based on SOA resort to interferometer XPM gates or the FWM effect. The following reported experimental achievements are worth highlighting: add-drop multiplexing from 160 to 10 Gb/s using a gain transparent UNI in [16].

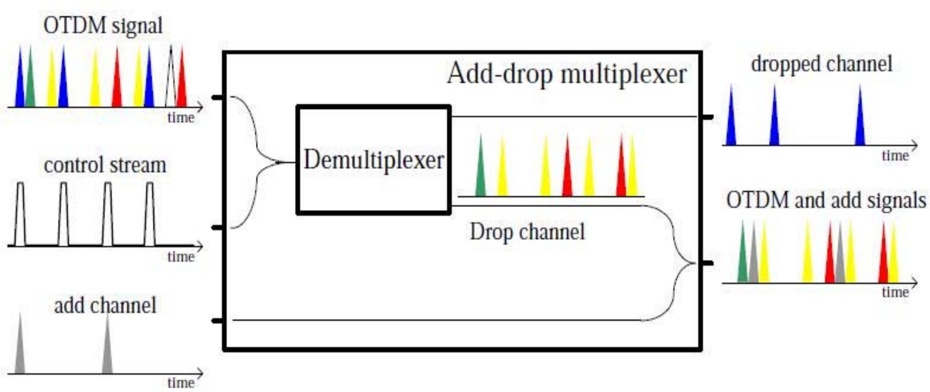


Figure 2-9: Schematic demonstration of the operation of a demultiplexer and an add-drop multiplexer. Different colours denote different sources of the OTDM signal.

Clock Recovery and Regeneration

Clock recovery and regeneration are detailed and studied in Chapter 5.

Pulse and modulation format conversion

Pulse Format converters are expected to be fundamental in the all-optical networks of the future, as different network scenarios require specific modulation and pulse formats [17].

Other applications

Besides the main applications described in the previous sections, SOA have also been employed in other applications, from which we highlight the following:

- Broadband light source using super luminescent light emitting diodes (SLED), which have basically the same structure as SOA;
- Continuous wave source, with experimental results of 50 wavelengths generation;
- Dispersion compensation using mid span spectral inversion through FWM;
- Short pulse generation, at high bit rates;
- Optical flip flops;
- Packet switches for optical packet switching (OPS) or optical burst switching (OBS) networks with contention resolution via wavelength conversion; or delay of contention packets in synchronous networks.

2.7 Summary

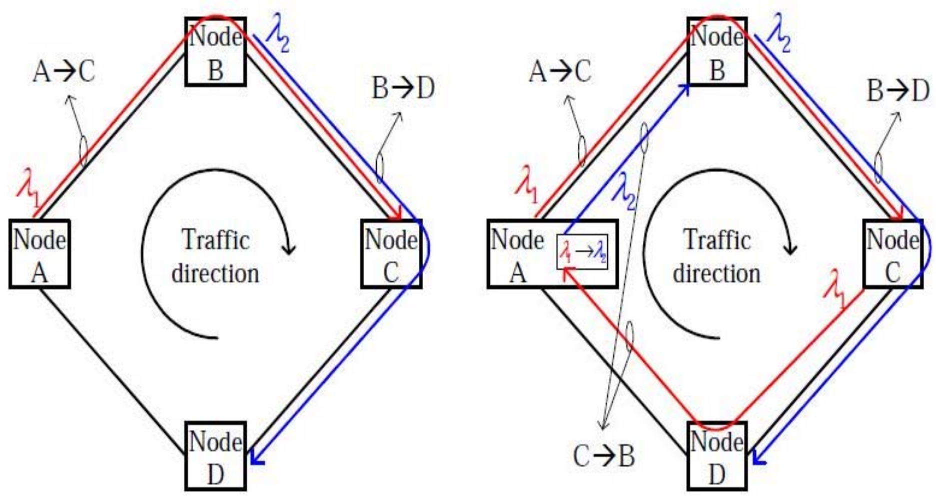
This chapter has presented an overview of the historical development of semiconductor optical amplifier (SOA) technology and the current-state-of the art including different materials and structures for the active layer, which determine the static and dynamic characteristics of SOA. SOA with specific design, such as reflective SOA, multi-electrode SOA, and gain-clamped SOA, have been presented as solutions for different applications.

The SOA gain and phase dynamics have been studied. The non-linear behaviour of SOA has been detailed, as it is the foundation of all-optical applications which will be studied throughout this work. The model considered for the simulation work has been presented, including intra- and inter-band effects. A state-of-the-art in terms of the most preeminent applications of SOA in optical networks has been presented, with particular relevance for non-linear applications.

Chapter 3

Wavelength conversion

Wavelength converters (WC) are essential devices in wavelength division multiplexed (WDM) optical networks, as they allow wavelength reuse, dynamic routing, and avoid wavelength blocking [18], increasing the network throughput. Figure 3-1 demonstrates, with a simple example, how wavelength converters can reduce network wavelength blocking. A uni-directional network with two available wavelengths, λ1 and λ2, receives three traffic requests: between A and C, B and D, and C and B. If wavelength conversion is not supported, a single wavelength must be continuously utilized end to end for each traffic request. After serving connections A→C and B→D, the network capacity is exhausted, as is exemplified in Figure 3-1a. If WC capabilities are available at node A, all traffic requests can be served, as illustrated in Figure 3-1 b.



a) Without WC capabilities;   *b) With WC capabilities at node A.*

Figure 3-1: Example of network capacity optimization through wavelength conversion (WC).

A wavelength converter is a device capable to shift one input signal at wavelength λ1 to another wavelength λ2, and is schematically illustrated in Figure 3-2. Wavelength converters can be divided in two groups [19]: optoelectronic WC (OEWC) and all-optical WC (AOWC). In OEWC the input optical signal at wavelength λ1 is detected, usually suffers regeneration, and is optically modulated using a laser with wavelength λ2. On the other hand, in AOWC all operations are performed in the optical domain: there is no OEO conversion. OEWC have reasonable deployment in optical networks; however, these are limited: OEWC present reduced transparency, and the costs increase with the bit rate and number of channels to be converted. Therefore AOWC have been intensively studied to avoid the so called "electronic bottleneck".

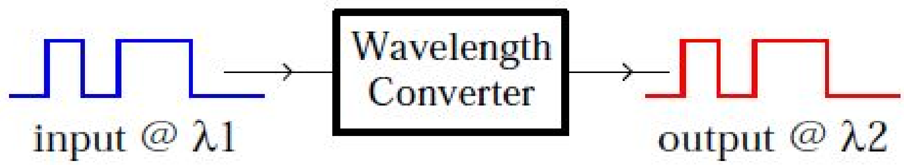


Figure 3-2: Schematic representation of a wavelength conversion.

Among the desired characteristics of a wavelength converter we highlight the following [18]:

- Bit rate independence;
- No extinction ratio degradation;
- Reduced signal to noise ratio degradation;
- Moderate input power required;
- Operation over a large input and output ranges of wavelengths;
- Operation over a large input power range;
- Low chirp;
- Simplicity;
- Polarization insensitivity.

Wavelength converters are of upmost importance since these also enable several other functionalities, such as optical logic or add-drop multiplexing of OTDM signals. Wavelength conversion in SOA is mainly achieved through one (or more) of the following non-linear effects:

- Cross gain modulation (XGM);

- Cross phase modulation (XPM);
- Cross polarization rotation (XPR);
- Four-wave mixing (FWM).

3.1 Technologies for Wavelength Conversion

As shown in the previous section, Wavelength conversion can find a broad field of applications in future optical networks. A natural question is which requirements these devices have to fulfill to be actually useful and which technologies provide the necessary features. Table 3.1 shows a list of rather general requirements and useful features for amplifying and wavelength converting devices as well as more concrete target specifications as they can be estimated from today's perspective. Of course, it is impossible to fulfill all specifications with a single device, so that, depending on the application, just a subgroup of the listed points will be important.

Table 3.1: Requirements for and features of amplifying and wavelength converting signal-processing devices

Requirement/feature	Target specification
transparency to variable bit rates	1 Tbit/s
transparency to amplitude and phase modulation format	16 QAM
ability for waveband conversion	
ability for phase conjugation	
wide wavelength tenability	> C-band
polarization independency	
high gain/conversion efficiency	30 dB
wideband flat gain/conversion spectrum	> C-band
low noise figure	3 dB
no amplitute or phase distortions	
low power consumption	

Table 3.2: Classification of wavelength converter

Concept	Nonlinear effects	Bit rate transparency	Modulation format transparency
Opto-electronic		NO	NO_1
Optical gating	XGM, XPM, saturable absorption, nonlinear loop mirror	Yes	NO_2
wave mixing	DFG	Yes	Yes
	FWM	Yes	Yes
	SPM	Yes	NO_3
	Electro-optic Effect	NO_4	Yes
	acousto-optic Effect	NO_5	Yes

1 A coherent transceiver consisting of a coherent receiver and an IQ-modulator can be used in principle as a modulation-format transparent opto-electronic wavelength converter, provided that appropriate and flexible electronic circuitry (e.g. software-defined) is used.

2 Recently, a modulation-format transparent wavelength converter based on XGM or XPM was proposed.

3 Not suitable for phase modulated signals due to generation of large excess phase noise

4 Because of small conversion bandwidth

5 Because of very small conversion bandwidth

Because optical signal processing is a very active field of research, it would be a desperate task to discuss the optimal technologies and devices for each application in detail. Thus, only some guidelines can be given. Among the requirements, the transparency regarding bit rate and modulation frequency are certainly at a very high priority in order to guarantee flexible use of the signal-processing device. Table 3.2 shows the classification of wavelength converting technologies after. Among the different types, only wave-mixing (i.e. parametric) wavelength converters based on four-wave mixing (FWM) and difference-frequency generation (DFG) provide modulation format as well as bit rate transparency explaining the particular interest in these concepts.

Table 3.3: Comparison of different wave mixing media

Process	Medium	Parametric amplification of CW signals	Suitable for photonics integration
FWM	silica/HNLF	Yes	NO
	soft glasses	No	NO
	InP/SOA	NO	Yes
	silicon waveguide	NO	YES
DFG	periodically poled lithiun niobate	No	YES

As DFG and FWM are nonlinear effects that originate from the $\chi2$ and $\chi3$ nonlinearity, respectively, they both occur in various media of which Table 1.3 shows a non-exhaustive list. The materials differ significantly in terms of e.g. linear and nonlinear loss and amount of Non- linearity leading to different device performance. Due to this, in particular the efficiency of the nonlinear effects differs significantly so that silica-based highly nonlinear fibers are the only 1 device that offers continuous-wave parametric amplification. Together with ultra-low splicing losses to a standard single-mode fiber, this fact also leads to a unique noise performance, as will be seen later on. With look on applications with many signal-processing devices, the suitability for integration is another natural distinctive criterion that plays a crucial role for the practicability and the commercialization perspective. As was made plausible by the short overview, FWM in HNLFs and in SOAs were identified at the beginning of this thesis as two of the most promising devices for parametric amplification and wavelength conversion. The HNLF offers the best performance in terms of efficiency and noise performance while the SOA offers photonic integration, in particular with the pump lasers, which presents an advantage over the silicon waveguide and the PPLN. However, as the work presented within this thesis mainly comprises analytical findings, it can be of course generalized to other media.

3.2 SOA-based wavelength converters

The wavelength converter is the most important device to avoid the unnecessary wavelength collision, to switch and reorganize signals in different directions, and to achieve the high flexibility in construction of OADM and OXC in WDM networks. Among the various kinds of wavelength converter, semiconductor optical amplifier (SOA)-based wavelength converters are worthy of notice in view of integration capability, compactness, and conversion efficiency. The SOA-based wavelength converters are representatively sorted into two types using the cross gain modulation (XGM) and the cross phase modulation (XPM). The SOA-based wavelength converter (WC) using XGM makes use of the dependence of the gain of an SOA on its input power. As the input power increased, the carriers in the gain region of the SOA get depleted, resulting in a reduction in the amplifier gain. The carrier dynamics within the SOA are very fast, happening on a pico-second time scale. Thus the gain responds in tune with the fluctuations in input power on a bit-by-bit basis. The XGM WC can handle bit rates as high as 10 Gb/s. Furthermore, it is turned out that the XGM WC can reach bit rates of 100 Gb/s with longer length of SOA. If a low-power probe signal at a different wavelength is sent into the SOA, it will experience a low gain when there is a high logic state in the input signal and a higher gain when there is a low logic state. This very same effect produces crosstalk when multiple signals at different wavelengths are amplified by a single SOA and makes the SOA unsuitable for amplifying WDM signals.

The XGM WC has the advantage that it is conceptually simple to assemble. It is polarization-insensitive because the gain of SOA is polarization-independent. However, there are several drawbacks, such as inversion of the pump input signal and the relatively large chirp of the probe output signal due to the large gain modulation. Additionally, the achievable extinction ratio (ER) is small (< 10 dB) since the gain does not really drop to zero when there is an input high logic state bit. The input signal power must be high (around 0dBm) so that the amplifier is saturated enough to produce a good variation in gain. This high-powered signal and probe are counter-propagating. Moreover, as the carrier density within the SOA varies, it changes the refractive index as well, which in turn affects the phase of the probe and creates a large amount of pulse distortion.

To sum up, the SOA-based WC using XGM, which is simply made up of a SOA, has the demerits that the wavelength-converted output signal is inverted with large chirp, low ER, and a lot of distortion. The same phase-change effect that creates pulse distortion in XGM can be used to effect wavelength conversion. As the carrier density in the amplifier varies with the input signal, it produces a change in refractive index, which in turn modulates the phase of the probe. This phase modulation can be converted into intensity modulation by using an interferometer such as a Mach-Zehnder interferometer (MZI).

Both arms of the MZI have exactly the same length and incorporate an SOA. The signal is sent in at one end and the probe at the other end. If no signal is present, then the probe signal comes out unmodulated. When the signal is present, it induces a phase change in each amplifier. The couplers in the MZI are designed with an asymmetric coupling ratio. This makes the phase change in each amplifier different. This results in an intensity-modulated probe signal at the output. To sum up, the SOA-MZI WC using XPM, which is composed of two SOA's in the structure of MZI, has the advantages that non-inverted output signal is achieved with high BER. However, it has a critical drawback that input power dynamic range (IPDR) is too narrow to be 3-4 dB at 10 Gb/s.

3.3 Wavelength Converters based on Four-Wave Mixing in SOA

3.3.1 General Characteristics

Four-wave mixing (FWM) is a nonlinear effect that takes place when two waves (signal and pump) at different wavelengths are injected into an SOA. A third optical field is generated at the device output, with frequency $\omega_c = 2\omega_p - \omega_s$

$\omega_c = \omega_p - \Omega$, where ω_p and ω_s are the frequencies of the pump and signal field respectively, and $\Omega = \omega_s - \omega_p$ is detuning between signal and pump.

Several physical phenomena can generate FWM in SOA. When detuning at the order of several GHz, the main mechanism is the carrier density pulsation induced by the signal-pump beating. The carrier density pulsation appears because of the stimulated emission. Our SOA component can handle generation mechanism of FWM.

The main advantage of frequency conversion based on FWM is independence of the modulation format and the bit rate. An additional advantage of this technique is the inversion of the signal spectrum and the resulting reversal of the frequency chirp. This property can be used to achieve dispersion compensation. The main disadvantage of the FWM converter is its low conversion efficiency.

3.3.2 Principle

A schematic of the wavelength converter configuration is depicted in Fig. 3.3. It consists of a Machzehnder interferometer (MZI) with SOA's inserted in the two arms as phase shifting elements. In order to use the configuration for wavelength conversion, asymmetry is required in the MZI, e.g., different splitting ratios in the couplers or asymmetric biasing of the SOA's. The operation is simple: CW light is injected into the MZI at the wavelength λ_1 (1543 nm**)** and a modulated signal laser is injected at wavelength λ_2(1531 nm)**,** and at the output of the converter it will experience constructive or destructive interference depending on the phase shift and variation of physical length of the SOA's. The SOA phase shift relies on the change in carrier density that can be controlled via the bias current or the optical input power (gain saturation). If optical power is injected into the MZI at λ_2 the carrier density in the SOA's will change due to the increased stimulated emission. Consequently, the phase, φ**,** and thereby the output power at λ_2, will change. So it is possible to vary the output power at λ_2**,** by varying the input power at λ_1; consequently, wavelength conversion is achieved. To analyze the results we use optical spectrum analyzer and BER analyzer.

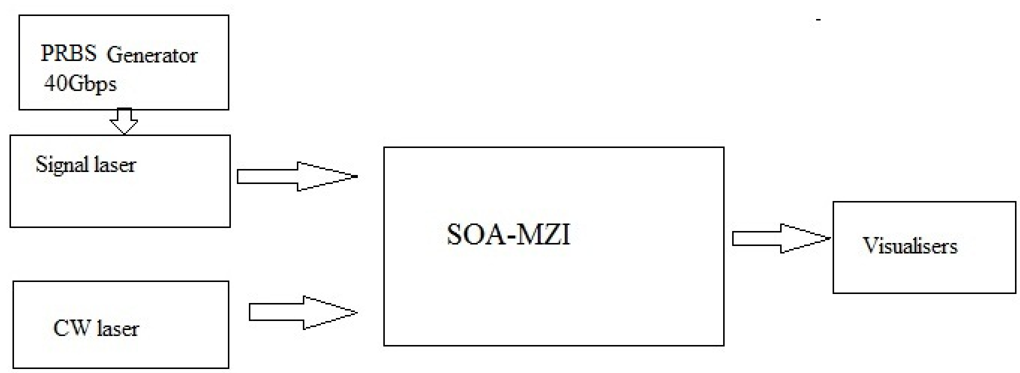


Fig 3.3: A schematic of the wavelength converter configuration.

Chapter 4

Fabry-Perot filter

The Fabry-Perot filter is an *optical resonator* that confines and stores light energy at selected frequencies. This optical transmission system incorporates feedback, whereby the light is repeatedly reflected within the system and thus circulates without escaping the system. A simple Fabry-Perot filter comprises of two parallel planar mirrors spaced a fixed distance apart. The rays travelling between the mirrors are kept perpendicular to the plane of the mirrors via a two-lens system. The lenses are placed outside the mirrors to serve two purposes: firstly, to establish parallel rays inside the *resonance cavity* between the mirrors; and secondly to focus the output light onto the detector following the Fabry-Perot filter. Further illustrations of this operation are given later. The basic parameters and figures of merit that are important for the design of this component are discussed. The chapter will conclude with a discussion of various sources of loss in Fabry-Perot filters and the effects of these losses on performance.

4.1 Historical Background

The Fabry-Perot filter was discovered by Charles Fabry and Alfred Perot at the University of Marseille in 1897. The discovery was a result from work primarily conducted in the field of electricity and the necessity in this field for precise measurements of small distances. With this study, Fabry and Perot discovered an optical phenomenon called *resonance* that led to the invention of a very useful method of measuring small distances. Fabry and Perot presented a mathematical model that described the peaks and the troughs of the resonance fringe pattern obtain from their optical resonator. The paper also presented a mathematical model for the transfer function of the resonance fringe pattern, based on Airy's formula [20]. In early 1899, the work of Fabry and Perot focused on studies in *interference* that led to the development of the *Fabry-Perot interferometer*.

In the years following 1902, the principle of interference between two plates had been well established by Fabry and Perot. Measurement techniques using this principle were rapidly deployed in other laboratories across Europe, because of the potential of precision associated with the techniques. In 1905, a full technique of *photographic recording*, attributed to Fabry and Perot was established and used extensively in many research institutions. The technique remained dominant for three decades until the introduction of photoelectric methods in the late 1940s. In recent years, the Fabry-Perot filter has found many uses in sensor and measurement applications. Christensen has demonstrated the use of the Fabry-Perot filter as a temperature sensor using multimode optical fibre. Valis and his co-workers have reported a Fabry-Perot filter designed from in-fibre mirrors for strain measurement. In the medical field the Fabry-Perot filter has been useful as a blood pressure and temperature sensor, as demonstrated by Van Brakel. The Fabry-Perot filter has also found applications in the design of multiplexer systems for local area network communications systems as reported by Saleh and Stone.

4.2 Figures of Merit

The figures of merit of the Fabry-Perot filter are performance criteria that determine the applicability of the device to a specified design. The figures of merit provide the framework for specification of design parameters of the filter. Before a discussion on the figures of merit can be initiated, it is necessary to take a closer look at equation

$$T_{15} = \frac{1}{1 + Fsin^2\theta_3}$$

F and θ_3 are the two variables that play a part in altering the properties of the transfer function of the Fabry-Perot filter. The contrast factor *F* was already linked to reflectance of mirrors R.

$$F = \frac{4R}{(1 - R)^2}$$

$$R = \frac{(r_{32} - r_{21})^2}{(1 + r_{32}\, r_{21})^2}$$

$$r_{ij} = \frac{n_i - n_j}{n_i + n_j}$$

where n_k is the index of refraction of layer k . r_{ij} is the reflection coefficient for light incident from layer *i* at the boundary with layer *j*

The parameter θ_3 , relating to the phase change associated with a traversal through layer 3. According to Keiser[21], for a standing wave to exist between two mirrors, as desired for Fabry-Perot oeration, the following phase change condition must hold:

$$e^{-2i\theta k} = 1$$

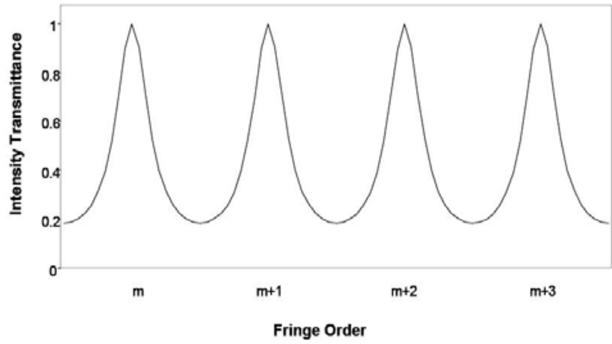


Figure4.1: Transmission of the Fabry-Perot filter as a function of frequency. Adjacent fringes are equally spaced in frequency.

where the angle associated with the phase change is defined as,

$$\theta_k = \frac{2\pi n_k d_k}{\lambda} \cos \varphi_k$$

where $\cos \varphi_k = 1$. The variables with subscript k are specific to the properties of the layer k. n is the index of refraction, d is the layer thickness, λ is the free space wavelength of the light wave and φ is the incidence angle. Assuming normal incidence (i.e. $\varphi = 0$) in the cavity

$$2\left(\frac{2\pi nd}{\lambda}\right) = 2\pi m$$

where m is an integer that defines the order of the transmission peaks existing in the Fabry-Perot filter. Since the free space wavelength is linked to the frequency via the speed of light c(i.e. $c = f\lambda$), then m can be written as a function of frequency as:

$$m = \frac{2nd}{c} f_m$$

Figure 4.10 shows a plot of the transmittance when the phase condition is met.

The various figures of merit discussed in this section affect different properties of the transmission pattern in Figure 4.1. These figures of merit are *Free Spectral Range (FSR)*, *Minimum Resolvable Bandwidth*, *Finesse* and *Contrast Factor*.

a. Free Spectral Range (FSR)

The free spectral range of the Fabry-Perot filter is the frequency spacing between two successive modes of resonance frequency (i.e. frequencies corresponding to maximum transmission). By considering two successive modes, represented by m and m-1 we have

$$m = \frac{2nd}{c} f_m$$

and

$$m - 1 = \frac{2nd}{c} f_{m-1}$$

Subtracting the two equations above yields

$$1 = \frac{2nd}{c} f_m - f_{m-1} = \frac{2nd}{c} \Delta f_{FSR}$$

and the free spectral range in terms of frequency becomes

$$\Delta f_{FSR} = \frac{c}{2nd}$$

Thus the free spectral range is a function of the physical mirror separation *d*. By accurately setting the variable d, the Fabry-Perot filter can be designed to a desired free spectral range.

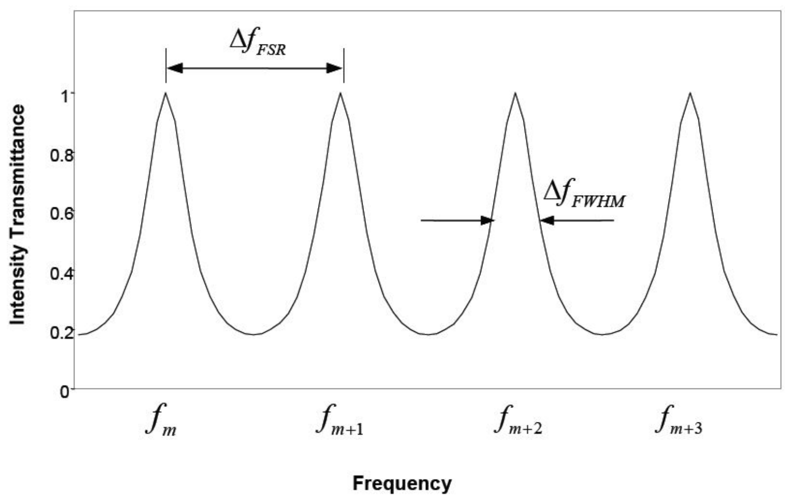


Figure 4.2: Transmission pattern of the Fabry-Perot filter indicating free spectral range and bandwidth resolution as functions of resonance frequency.

b. Minimum Resolvable Bandwidth

The minimum resolvable bandwidth Δf_{FWHM} , also known as the *fringe width* or the *resolution bandwidth*, is the width (i.e. full width at half maximum peak intensity) of the standing wave generated during the operation of the Fabry-Perot filter. The minimum resolvable bandwidth is an important figure of merit in the design of Fabry- Perot filters. Low values of Δf_{FWHM} are often desirable in the design of these devices. The minimum resolvable bandwidth relates to both the reflectance of the Fabry-Perot mirrors and the mirror separation. This figure of merit is set by the designer during the design process of the Fabry-Perot filter.

c. Finesse

The finesse is an important parameter that determines the performance of a Fabry- Perot filter. Conceptually, finesse can be thought of as the number of beams interfering within the Fabry-Perot cavity to form the standing wave. A higher finesse value indicates a greater number of interfering beams within the cavity, and hence a more complete interference process. In its simplicity, the finesse is defined as the ratio of the free spectral range and the minimum resolvable bandwidth as,

$$F_r = \frac{\Delta f_{FSR}}{\Delta \mathrm{f}_{\mathrm{FWHM}}}$$

The primary factor that affects finesse is the reflectance *R* of the Fabry-Perot mirrors, which directly affects the number of beams circulating inside the cavity. The finesse as a function of the reflectance is defined as[16],

$$F_r = \frac{\pi\sqrt{R}}{1 - R}$$

This indicates that the finesse can be increased simply by increasing the reflectance of the mirrors. However, the consequence of this increase in reflectance results in the reduction of light transmitted by the Fabry-Perot filter. Figure 4.3 shows the effect of finesse on the transmission of the Fabry-Perot filter. In addition to the mirror reflectance, other factors that affect the finesse include the mirror surface quality, temperature variations and loss factors associated with the design.

d. Contrast Factor

The contrast factor *F*, is another figure of merit that is important for the design of Fabry-Perot filters. The contrast factor is defined primarily as the ratio of the maximum to minimum transmission (i.e. the ratio in the intensity transmission values of the peaks and the troughs shown in Figure 4.12) as follows:

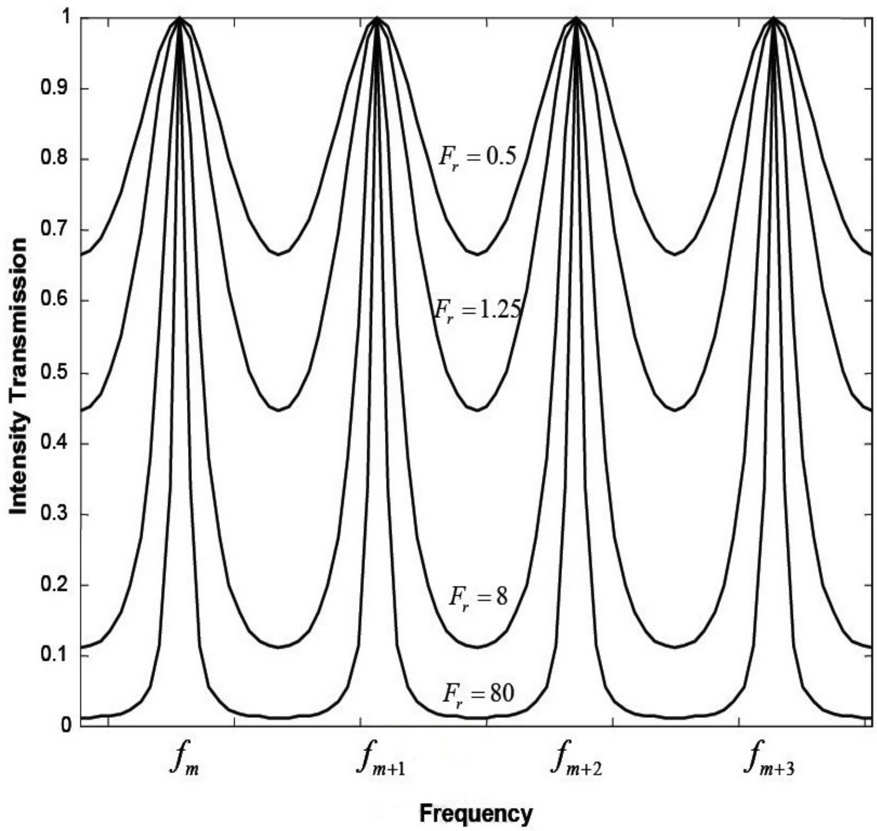


Figure 4.3: Variation of transmission intensity of the Fabry-Perot filter for different values of finesse.

$$F = \frac{T_{max}}{T_{min}}$$

Like the finesse, the contrast factor is directly related to the reflectance of the Fabry-Perot mirrors.

4.3 Losses in Fabry-Perot Filters

Up to this point in the discussion on the Fabry-Perot filter an ideal, lossless device has been assumed. However, practical Fabry-Perot devices are governed by various loss elements that limit the expected performance of the device. The presence of loss implies a need to overestimate design parameters in order to meet the desired performance specifications. However, overcompensation for losses in the design may render unnecessary expenses associated with the cost of the device. It is therefore important to establish the sources of loss and assess their impact on the performance of the Fabry-Perot filter.

4.5.1 Sources of Loss

The sources of loss in Fabry-Perot filters can be classified into two distinct categories:

- Losses attributed to the absorption and scattering of the media that surround the mirrors.
- Losses arising from imperfect reflections at the mirror of the Fabry-Perot filter. Non-ideal mirrors cause the light to be partially transmitted through the mirrors and the cavity, compromising performance.

The first category of losses mentioned above depends specifically to the type of design deployed for the Fabry-Perot device. Stone and Stulz[22] have identified such losses in optical fibre-based Fabry-Perot interferometer designs. The losses specific to fibre-based Fabry-Perot devices as presented by Stone and Stulz are as follows:

1. Mirror displacement diffraction loss
2. Angular misalignment loss
3. Lateral offset loss
4. Loss due to curvature of the endface

Chapter 5

Optical regeneration

With the outcome of the EDFA and dispersion compensation techniques, transmission of optical signals over hundreds or thousands of kilometers became possible without intermediate OEO regenerators. The increasing demand for optical bandwidth has lead to the development of WDM systems and to the increase of the per channel bit rate. In parallel to the explosion of per channel bit rates and transmission distances, optical systems are also evolving from simple transmission systems to a higher level of complexity, where switching and signal processing is supported by the optical layer. By eliminating the *electronic bottleneck*, all-optical signal transmission and processing are expected to enable the next generation of optical networks, by dramatically reducing costs, energy consumption, and increasing the network throughput. The increase of the per-channel bit rate usually leads to a reduction of the signal tolerance to optical impairments. Such optical impairments are mostly originated from propagation and from signal processing. Propagation degrades the optical signal due to various distortion sources; such as: uncompensated chromatic dispersion, polarization mode dispersion, non-linear effects, or noise accumulation. Optical signal processing degrades the signals by tight optical filtering; crosstalk in photonic-cross connects; polarization dependent losses (PDL) of components; and by imperfect optical functionalities, like wavelength or format conversion. Usually, signal distortion is divided in two main categories [24]: amplitude distortion, and temporal distortion. *Amplitude distortion* degrades the contrast between logical '1' and '0; while *temporal distortion* refers to temporal fluctuations between optical pulses (also known as phase timing jitter).

Signal degradation in optical systems is typically overcome by adding regeneration stages at periodic transmission distance intervals. The most common type of regeneration consists in detecting the optical signal, recovering it in the electrical domain and retransmitting it. However, this technique suffers from the general disadvantages of OEO signal processing. On the other hand, all-optical regenerators are expected to overcome the drawbacks of OEO converters and are considered essential elements for fully-functional optical networks; however, all-optical regeneration at high bit rates is still a research topic.

Regeneration can be divided in the three main functionalities of Figure 5-1: re-amplification, re-shaping, and re-timing. The simplest functionality is *re-amplification* (or 1R), which consists in simple optical amplification. A device which also provides *reshaping* in addition to *re-amplification* is known as 2R. *Re-shaping* consists in increasing the contrast between the two logical levels; which improves the required optical signal to noise ratio (OSNR) for a specific bit error rate (BER) level. Finally, 2R is combined with *re-timing*, to create a full 3R. Re-timing refers to the reduction of the signal jitter.

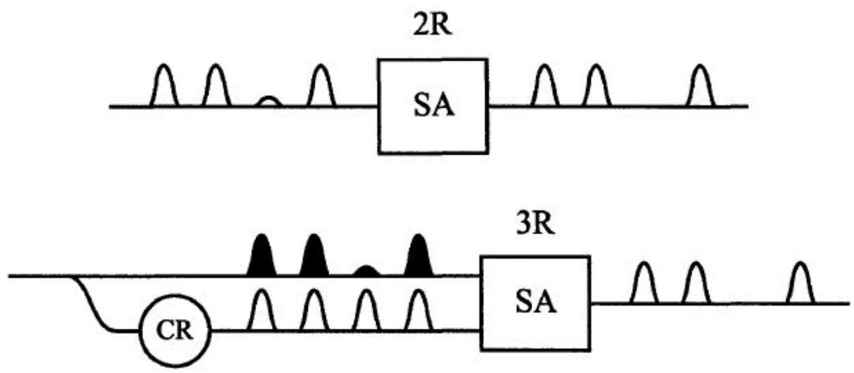


Figure 5-1: Illustration of the basic regeneration.

Section 5.2 reviews the state-of-the-art in all-optical regeneration using SOA based devices. Section 5.3 reports for the first time to the author's knowledge regeneration of coherent optical code division multiple access (OCDMA) signals with distortion provoked by multiple access interference (MAI). The regeneration scheme is based on a Machzehnder interferometer exploiting cross phase modulation in semiconductor optical amplifiers. Experimental regeneration of an 8 Chip 10 Gb/s OCDMA signal is demonstrated with improvements in the required optical signal to noise ratio and elimination of bit error rate floor. This work has been presented in [26].

5.1 All-optical regeneration techniques in SOA

Figure 5-2 depicts the basic all-optical 3R scheme [27]-[29]. The input signal is split in two replicas; one of the replicas feeds a clock recovery sub-system, which produces stable optical pulses with reduced jitter. The second input signal replica is then used to control a non-linear gate, which encodes the logical information in the optical clock signal. Usually 3R features also wavelength conversion, as the output signal wavelength is the same of the clock signal. This scheme only supports on-off keying input signals. The two main building blocks of Figure 5-2 are revised hereafter.

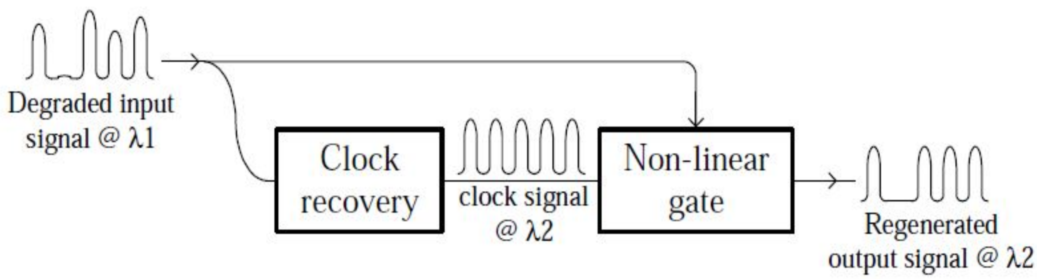


Figure 5-2: Common all-optical 3R scheme.

5.1.1 Non-linear gate

In an optical regenerator, the non-linear gate is responsible for the *re-shaping* functionality. Therefore, non-linear gates are employed in 2R and in 3R. Figure 5-3 illustrates the conceptual transfer function of such non-linear gate [30]. The input signal is improved in two distinct manners. First, signal improvement is achieved through an increase of the ER; obtained by the steep slope of the transfer function between the logical '0' and '1' of the input signal. Second, fluctuations in logical '0' and '1' levels are reduced by the approximately constant output power over input logical '1' and '0'. Such re-shaping functionality is similar to that performed in electronic decision circuits, present in most opto-electronic regenerators. The main drawback of the decision circuit like transfer of Figure 5-3 is that input amplitude noise is converted in output timing jitter [30]; therefore, in 2R regeneration there is a trade-off between amplitude regeneration and output jitter degradation.

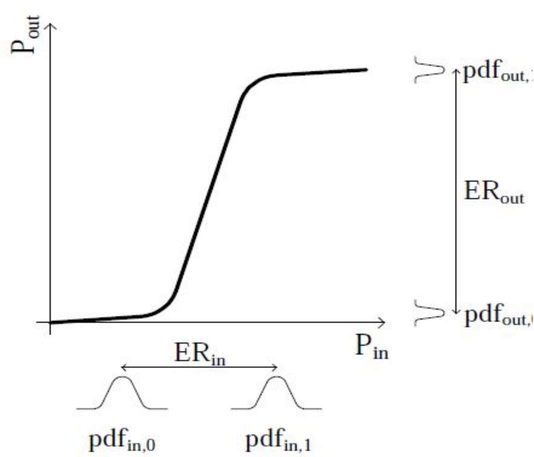
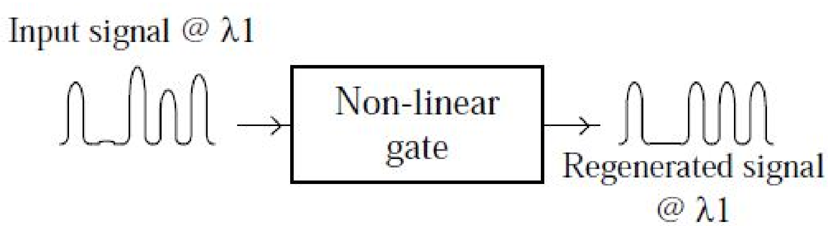


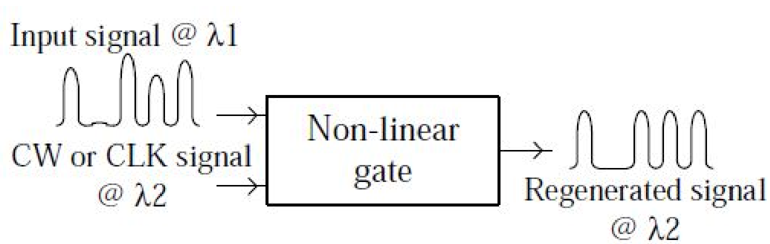
Figure 5-3: Transfer function of non-linear gate. Pin and Pout: input and output power; pdfi: probability density function; ERin and ERout: input and output extinction ratio.

Optical 2R and 3R regenerators with non-linear gates such as the one illustrated in Figure 5-3 do not necessarily allow recovering from errors in the input signal: the input BER is not improved. Therefore, 2R and 3R should be periodically employed over the signal transmission line to decrease the error accumulation with further transmission.

Optical re-shaping requires a scheme to provide the non-linear transfer function depicted in Figure 5-3. SOA can be employed to achieve such purpose through one of two means: directly using the SOA non-linear intensity transfer function, which arises from carrier density modulation; and recurring to the non-linear transfer function of a scheme employing SOA. SOA-based non-linear gates are usually divided in two groups: pass-through, and wavelength-conversion, as depicted in Figure 5-4 [31]. In pass-through schemes, the input signal is self-modulated at the SOA-based regenerator; as a consequence, the output and input signal wavelengths are the same. Pass-through regenerators can only perform 2R. In wavelength-conversion schemes, the input signal at λ1 is fed to the non-linear gate together with a CW signal or an optical clock signal (CLK) at λ2. The non-linear transfer function is applied from the input signal at λ1 to a local wavelength, λ2. The input signal is also known as *control-signal*. Such non-linear gates are appropriate for both 2R (when the signal at λ2 is a CW) and 3R (when the signal at λ2 is an optical clock).



(a) pass-through



(*b) wavelength-conversion*

Figure 5-4: Use of non-linear gates in pass-through and wavelength-conversion schemes.

One of the most common regeneration schemes with SOA is based on MZI-SOA devices, which is a wavelength-conversion scheme. This basic regeneration scheme is similar to the wavelength conversion scheme of Figure 3-1. To understand the principle behind regeneration in MZI-SOA structures, consider the conceptual schematic of Figure 5-5, which depicts an interferometer with a non-linear medium in one of the arms. The input signal at λ1 is the control signal of the non-linear medium and the CW signal at λ2 is the local probe wavelength. Considering that the nonlinear medium response to a control signal is a phase modulation of the probe signal:

$$E_{probe,out} = E_{probe,in}\, e^{(j(\alpha p_{ct1}+\Phi))}$$

Where *Eprobe,out* and *Eprobe,in* are the electrical fields of the input and output optical signals, *Pct1* is the power of the control (information) signal, and α and Φ are constants.
The interferometer output power is then given by:

$$P_{probe,out} = \frac{P_{probe,in}}{4}(1+\cos(\alpha P_{ct1}+\Phi))$$

Where *Pprobe,in* is the CW signal input power, and *Pprobe,out* is the output power at the CW signal wavelength.

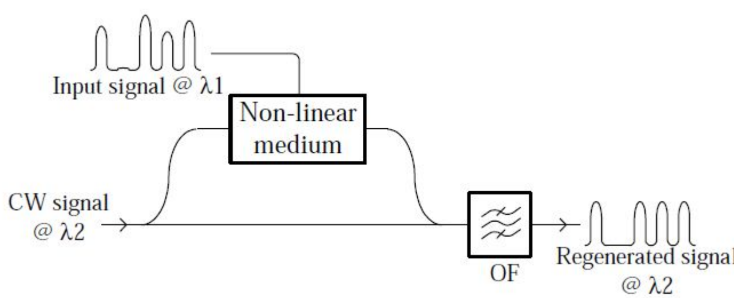


Figure 5-5: optical 2R regeneration via interferometric scheme.

Figure 5-6 exemplifies the static power transfer function of an interferometric gate, similar to Figure 5-5, when parameters α and Φ are optimized to obtain optimum regeneration characteristics. It can be verified that such transfer function reshapes the input signal, since for logical ‘0’ and ‘1’ the input power can vary by +/- 10% around the nominal logical level and the output power only varies by +/- 2.5%. Cascading two of these interferometric gates results in further improvements of the 2R characteristics: with two gates the input signal power at each logical level can vary by +/- 15% with only +/- 2.5% of output power variation.

Hence, MZI-SOA is excellent to implement non-linear gates with regeneration, and have been simulated in this thesis with single MZI-SOA. MZI-SOA can also be used in pass through configurations, provided that the parameters of the system are optimized.

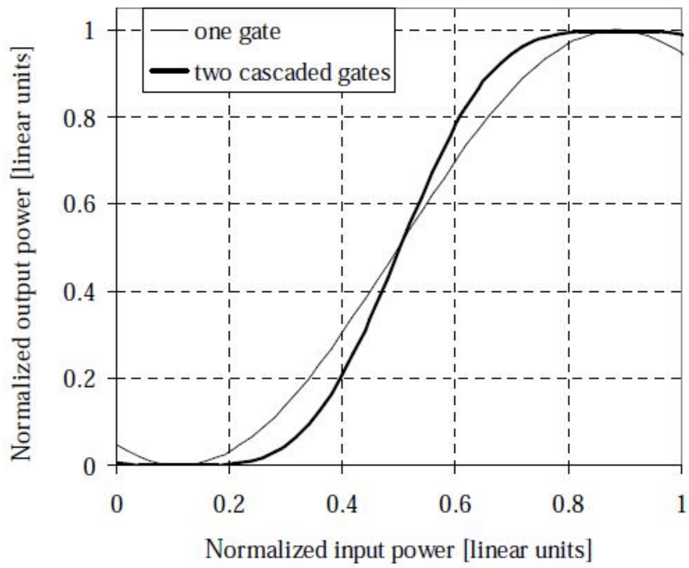


Figure 5-6: Characteristic of non-linear gate similar to Figure 5-5, when the signal passes by one gate, and by two cascaded gates.

5.1.2 Clock recovery

Clock recovery is a key element to achieve 3R operation as it performs the *re-timing* functionality. One approach for the clock-recovery subsystem is to use electro-optical schemes; the other is to use an all-optical scheme. All-optical 3R can employ electro-optical schemes to achieve clock-recovery without losing the *all-optical* label. All optical 3R allows some electronic processing, provided that such processing is narrowband, as is clock recovery. However, electro-optical schemes have higher power consumption and costs; therefore, all-optical clock recovery is generally preferred.

5.1.3 Operation of All-optical clock recovery using single SOA

All-optical SOA based schemes to extract optical clock include the use of a FPF and a single SOA [25]. All-optical clock recovery can be achieved through extracting the clock spectral components from optical signals with narrowband optical filtering. A Fabry-Perot filter (FPF) with a free spectral range (FSR) matched to the signal bit-rate, and a relatively large finesse (typically >100) works effectively in this situation. Fig. 5-7 explains the operation principle of the all-optical clock recovery module that is built with a FPF and a semiconductor optical amplifier (SOA). The optical spectrum of the return-to-zero (RZ) signal consists of continuous spectral components from data modulation and line spectral components from the clock and its harmonics. When passing through the all-optical clock recovery module, the clock spectral components get transmitted, while the data modulation components get suppressed.

The FPF removes most of the data modulation and provides optical clock pulses matching to its FSR (i.e. signal bit-rate) frequency. Clock decays due to the presence of 0's that can be improved by using SOA-MZI at the input. Actually, SOA add 1's at the place of 0's.We have used the commercial software Optisystem from *Optiwave, Inc.*, which allows the simulation of a transmission link at 40 Gbit/s. The clock recovery setup is shown in Fig. 5-7. It is composed of an FPF followed by an SOA in output power saturation regime. Fig. 5-7 depicts the spectrum of the input optical signal, consisting of a continuous spectrum and discrete lines; the periodic filter transfers function that allows a filtering of the discrete lines of the spectrum if the FSR is close to the frequency modulation (bit rate). The filtered spectrum of the Recovered Clock is also depicted.

These basic spectra are obtained using our simulation results and put in evidence the filtering process based on the extraction of the modulation from the data spectrum. It appears that the quality of the Recovered Clock depends intrinsically on filter characteristics, and particularly on the finesse value. The filter being not ideal, a residual part of the continuous spectrum is transmitted and present in the output spectrum.

The number of bits per sequence was varied from $2^7 - 1$ to $2^{13} - 1$ (i.e., 127–8191 bits/sequence) at a bit rate of 40 Gbit/s. We were unable to simulate longer sequences because of the limitations of our computational equipment. The physical parameters used for the simulation are: the SOA input power equal to 2.4 dBm, the SOA current drive equal to 300 mA, the SOA length equal to 500 μm, the effective area equal to 2.4 × 10−13 m2 , and the confinement factor equal to 0.3.

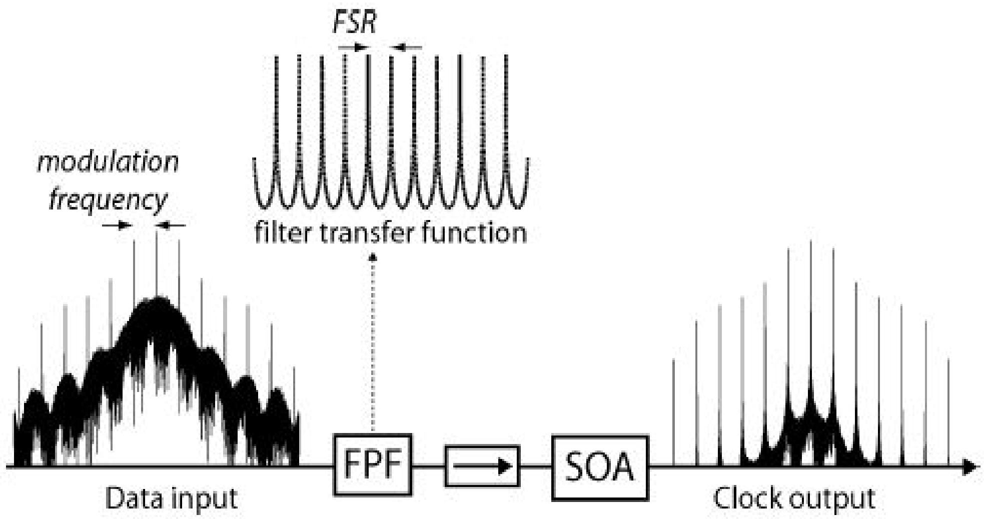


Figure 5-7 Operation of optical clock recovery using single SOA [25].

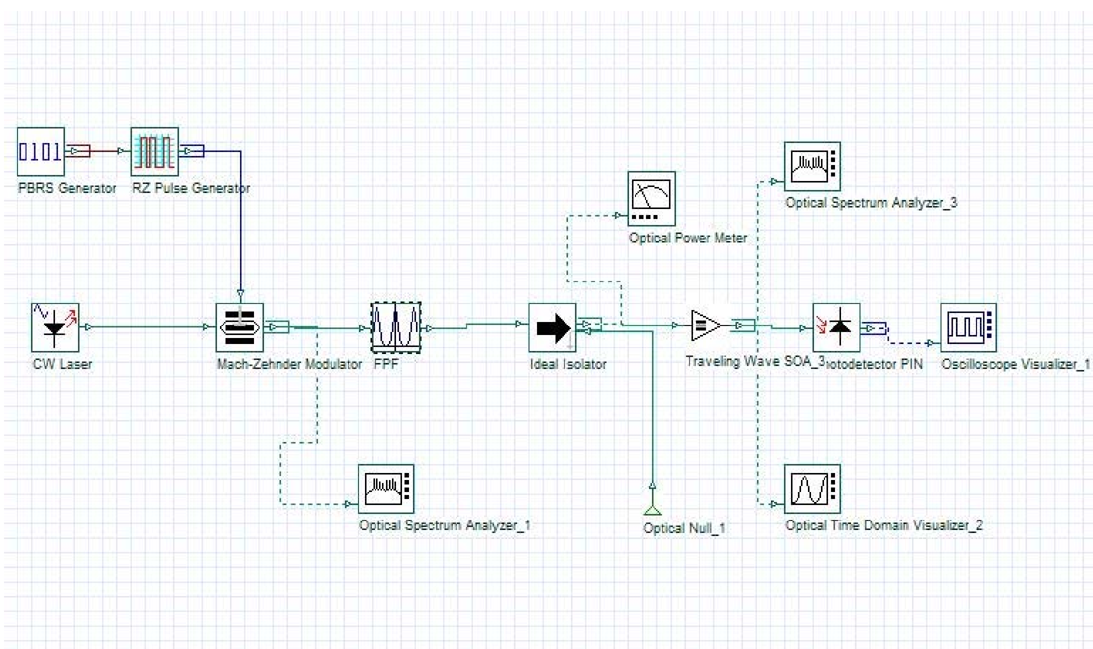
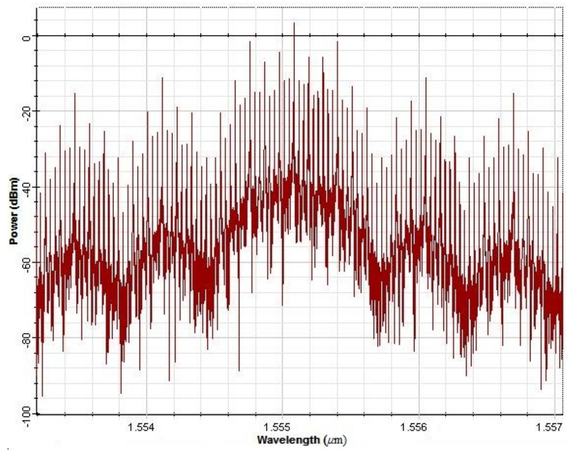
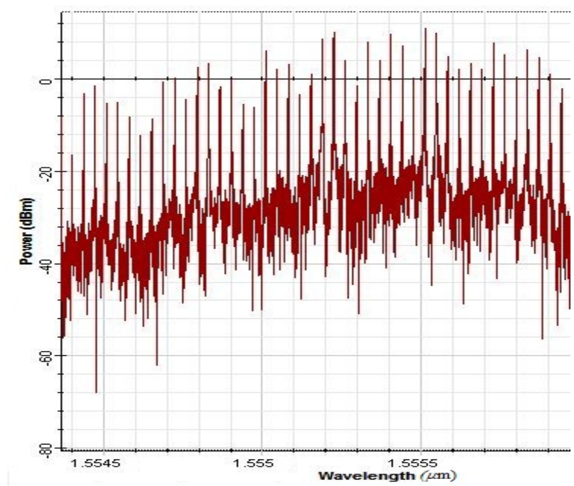


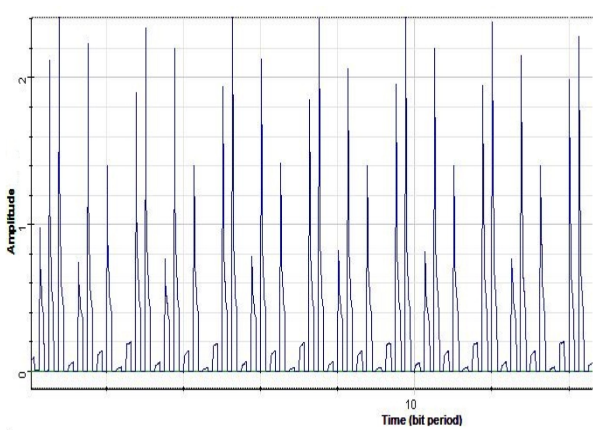
Figure 5-8 Operation of optical clock recovery using Optisystem software.



(a)



(b)



(c)

Figure 5-9 (a) input data spectrum (b) clock spectrum(c) clock recovered.

5.1.4 Operation of All-optical clock recovery using SOA-MZI

5.1.4.1 SOA-MZI

Semiconductor optical amplifier-Machzehnder interferometric (SOA-MZI) switches have been established as the mainstream solutions when high-speed optical signal processing applications are targeted, mainly as a result of their proven credentials in a multiparametric operational framework. This framework has been primarily shaped by the needs and challenges of today's routing and processing tasks in short-range optical interconnect architectures, requiring ultrafast processing capabilities, increased integration densities, increased power consumption efficiencies, as well as generic building blocks performing in multiple processing functionalities and being capable of operating in cascades. In this way, SOA-MZIs fulfill the requirement for ultrafast line-rate processing directly in the optical domain as they are indeed high-speed switching elements, whereas they have also performed successfully in several functional and highly useful applications with completely different characteristics [23]. Besides being utilized in so-called traditional applications like demultiplexing, wavelength conversion (WC), optical logic and regeneration, they have been exploited as key elements in challenging functionalities including packet envelope detection (PED), clock recovery (CR) and burst-mode reception [23]. Their enhanced multifunctional architectural potential is even more pronounced when operating in coupled configurations, as they have led optical circuitry to highly promising optical buffering solutions [23]. Moreover, SOA-MZIs have been shown to operate in cascaded stages, enabling the deployment of complex all-optical processing systems, accommodating at the same time transparency in optical networks.

One simple method to recover the clock signal is presented in Figure 5-10 [25]. The clock-recovery consists in a first stage, where the information signal is wavelength converted in an MZI-SOA. The converted signal is filtered with a Fabry-Perot filter (FPF), which extracts the clock components of the converted signal. The power of the pulses at the FPF filter output fades exponentially for consecutive '0' of the input signal. Therefore, a second MZI-SOA wavelength conversion stage is used to equalize the power of the optical pulses. The first wavelength conversion stage could potentially be omitted; however, since the FPF central frequency must be tuned with the input wavelength, wavelength tracking would be required.

The clock recovery scheme based on SOA-MZI with FPF has great potential due to its simplicity, and very fast clock acquisition time, which is very useful in packet or burst applications, for example

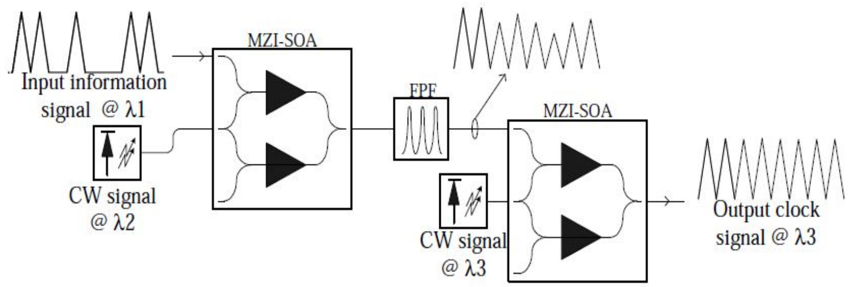


Figure 5-10: Clock recovery circuit using MZI-SOA and Fabry-Perot filter.

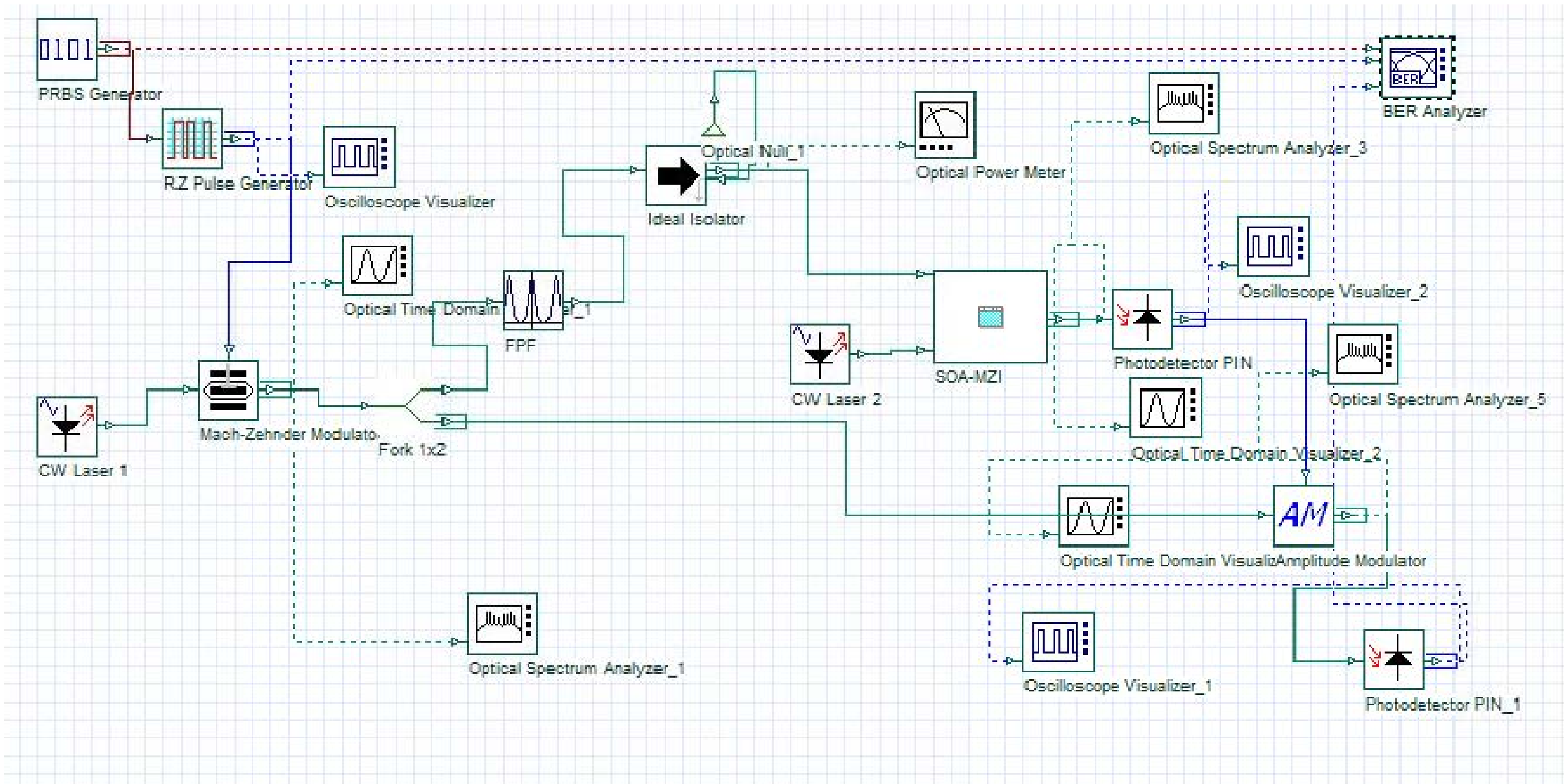


Figure 5-11: Operation of All-optical wavelength regeneration using SOA-MZI

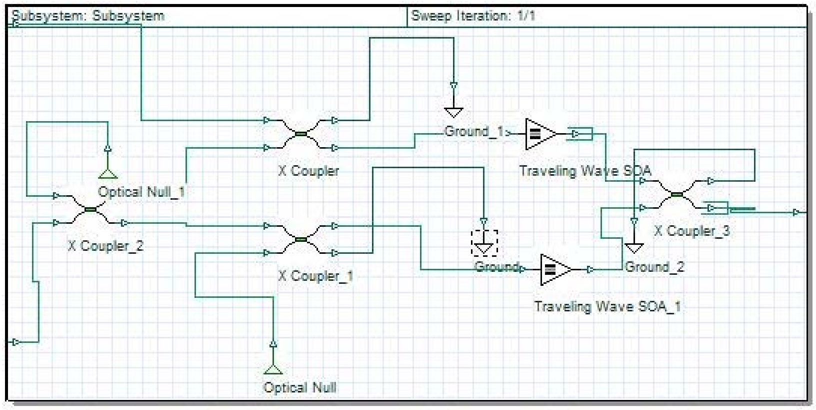
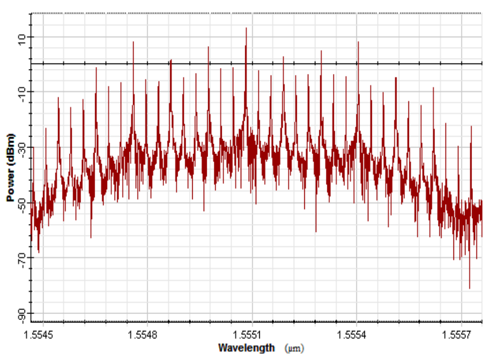
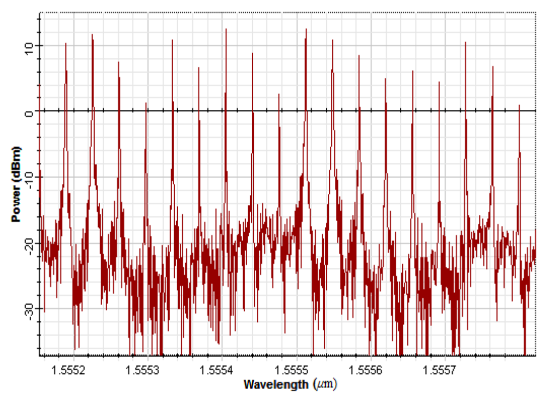


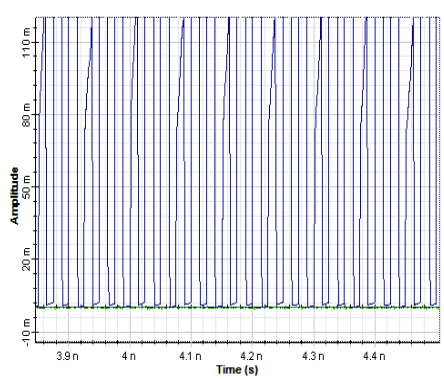
Figure 5-12: SOA-MZI



(a)



(b)



(c)

Figure 5-13: (a) input data spectrum (b) clock spectrum(c) clock recovered.

On comparing, The Results of clock recovered from Fig. 5-8 and Fig. 5-11, we can observe that clock recovered from single SOA decays much more than that of using SOA-MZI. The amplitude varies slowly and at large sequences of 0's, Amplitude of clock is high than single SOA. The BER of single SOA varies between e^{-13} to e^{-18} while BER of SOA-MZI varies between e^{-28} to e^{-32} on the basis of presence of 1's and 0's in the PRBS generated sequences.

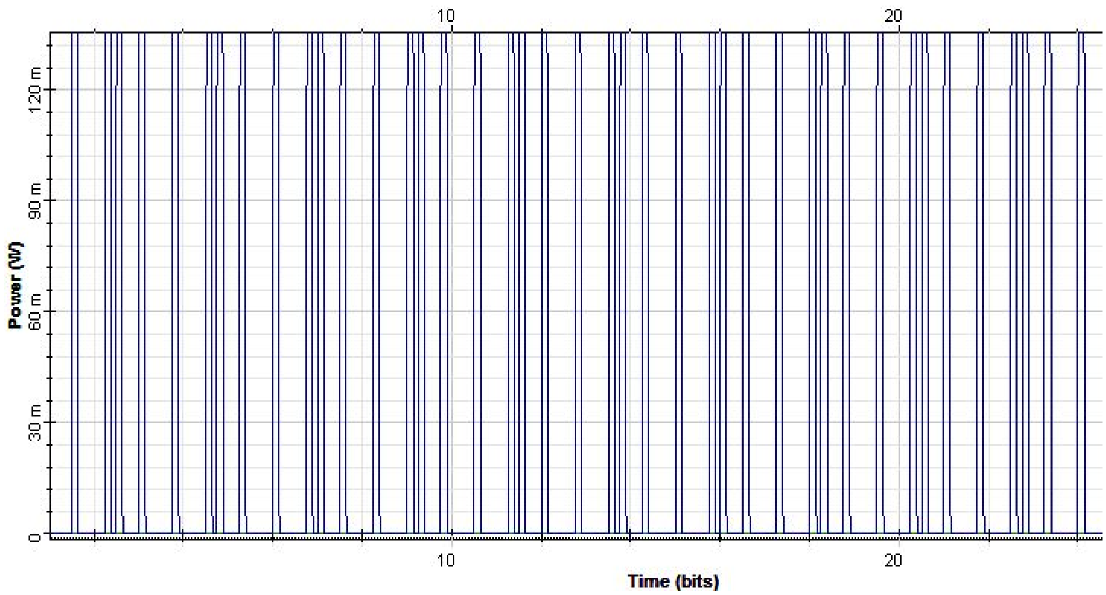


Figure 5-14: optical input data pulses.

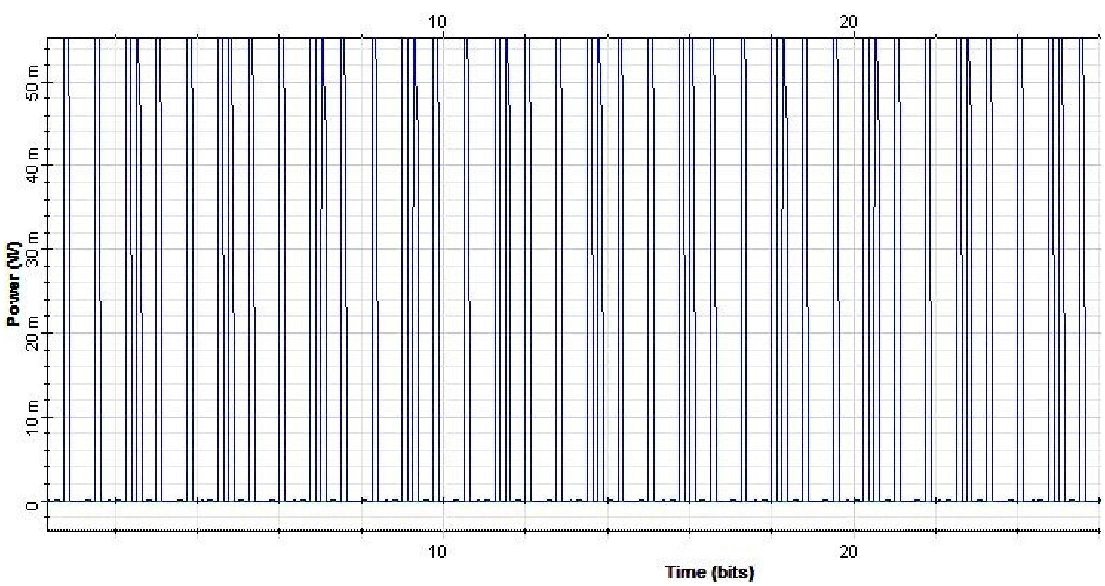


Figure 5-15: Regenerated optical data pulses.

Chapter 6

Conclusion

We have studied the nonlinear properties of SOA and its use in machzehnder configuration. Also we have demonstrated and simulated 40 Gbps all-optical wavelength regeneration by SOA's in a machzehnder configuration using OptiSystem. We have presented 40 Gbps wavelength regeneration with power penalties of less than 2.5 dB and BER of less than e^{-30}. It is found that system is transparent of bit format. Working together with a FPF-based all-optical clock recovery module, this technique achieved modulation-format-independent all-optical clock recovery with a simple and straight-forward configuration. When the data modulation contents long sequences of repeated zeros, the recovered clock amplitude can decay due to pattern-dependence. By using SOA in machzehnder configuration, we can improve recovered clock. The simulation results showed that the SOA-MZI could sharpen the clock components in the input signal and reduce both the timing jitter and amplitude fluctuations on the recovered clocks. It is expected that further improvements are possible if two cascaded MZI-SOA stages are employed and high bit rates are possible by using gain-clamped SOA.

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