ALL-OPTICAL 2R REGENERATOR BASED ON SELF-PHASE MODULATION

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I dedicate this thesis to my lovely husband,

Mohd Khairul Fahmi Bin Jusoh

To my beloved parents,

Hj Mat Yaacob Bin Mat Som and Hjh Hanisah Binti Hj Mohamed

To my dearest siblings,

Saripah

Shuhaimi

Sarimah

Sakinah

Miswary

Siti Shalwani

Mohd Khairul Aswan

Mohd Rizal

Siti Sarah

May this thesis will give inspiration to my adorable nieces and nephews

To my late grandmother, Lijah Binti Junuh…Al-Fatihah

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ABSTRACT

Nowadays, optical regeneration is getting popularity as it provides an effective way of coping with transmission impairment. Transmission impairments degrade the quality of optical signals and thus, ultimately limiting the achievable transmission distance. Optical 2R regenerators provide an effective way of coping with transmission impairments by restoring the quality of optical signals through re-amplification and reshaping (2Rs), thereby enabling reliable transmission over long distances. In this work, All-Optical 2R Regeneration which is based on self-phase modulation (SPM) in a single highly nonlinear fiber (HNLF) with 2500 km length of transmission is investigated. In addition, there are two types of modulation format namely, non-return-to-zero on-off keying (NRZ-OOK) and return-to-zero on-off keying (RZ-OOK) were investigated. Both of these modulation techniques were performed in two stages which are the degradation and regeneration stages. The simulation results show that the NRZ-OOK and RZ-OOK have significant improvement after the regeneration stage. For NRZ-OOK, the maximum Q-factor before and after the regeneration stage are 3.751 and 5.859, respectively. The minimum bit error rate (BER) after the degradation stage is 10^{-5} and is further improved to 10^{-9} after the regeneration stage. For RZ-OOK, the maximum Q-factor before and after the regeneration stage are 4.514 and 6.768, respectively. The minimum bit error rate (BER) after the degradation stage is 10^{-6} and is further improved to 10^{-12} after the regeneration stage.

ABSTRAK

Pada masa kini, pertumbuhan semula isyarat optik menjadi lebih popular kerana kelebihannya yang menawarkan cara yang lebih berkesan bagi mengatasi kemerosotan penghantaran isyarat. Kemerosotan penghantaran isyarat merendahkan kualiti isyarat optik, dan akhirnya menghadkan pencapaian jarak penghantaran. Penjanaan semula isyarat optik 2R menyediakan cara yang lebih berkesan dalam menangani kemerosotan penghantaran dengan memulihkan kualiti isyarat optik melalui penguatkuasaan semula dan pembentukkan semula (2Rs), sekaligus membolehkan penghantaran dicapai pada jarak yang lebih jauh. Dalam kajian ini, pertumbuhan semula isyarat optik 2R berdasarkan fasa modulasi sendiri di dalam gentian optik tidak linear dengan 2500 km jarak penghantaran telah di kaji. Tambahan pula, terdapat dua jenis teknik modulasi yang digunakan dalam kajian ini iaitu isyarat tidak kembali kepada sifar (NRZ-OOK) dan isyarat kembali kepada sifar (RZ-OOK). Teknik modulasi ini dilaksanakan dalam dua peringkat iaitu peringkat degradasi dan peringkat pertumbuhan semula. Keputusan simulasi menunjukkan bahawa NRZ-OOK dan RZ-OOK mempunyai peningkatan yang ketara di peringkat pertumbuhan semula isyarat. Bagi NRZ-OOK, maksimum faktor-Q sebelum dan selepas pertumbuhan semula masing-masing adalah 3.751 dan 5.859. Manakala kadar minimum ralat bit di peringkat degradasi adalah 10^{-5} dan meningkat kepada 10^{-9} di peringkat penjanaan semula. Bagi RZ-OOK pula, maksimum faktor-Q sebelum dan selepas pertumbuhan semula adalah 4.514 dan 6.768 manakala kadar minimum ralat bit adalah 10^{-6} di peringkat degradasi dan meningkat kepada 10^{-12} di peringkat penjanaan semula.

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LIST OF SYMBOLS AND ABBREVIATIONS

n	-	Fiber refractive index
I	-	Optical intensity
n_o	-	Ordinary refractive index
γ	-	Nonlinear coefficient
λ	-	Wavelength
A_{eff}	-	Effective area
L_{eff}	-	Effective length
V_s	-	Velocity
V_2	-	Maximum signal voltage
V_1	-	Noise margin
ΔT	-	Distortion at zero crossing
D	-	Dispersion
P_o	-	Peak power
ASE	-	Amplified Spontaneous Emission
BER	-	Bit Error Rate
CW	-	Continuous Wave
DCF	-	Dispersion Compensating Fiber
DGD	-	Differential Group Delay
DSF	-	Dispersion Shifted Fiber
EAM	-	Electro-Absorption Modulator
EDFA	-	Erbium Doped Fiber Amplifier
FBG	-	Fiber Bragg Grating
FOPA	-	Fiber Optic Parametric Amplifier
FOPO	-	Fiber Optic Parametric Oscillator

FPF	-	Fabry Perot Filter
FSR	-	Free Spectral Range
FWM	-	Four Wave Mixing
HNLF	-	High Non-Linear Fiber
MLL	-	Mode Lock Laser
MZM	-	Mach Zehnder Modulator
NRZ	-	Non Return Zero
NLPN	-	Non-Linear Phase Noise
OBPF	-	Optical Band-Pass Filter
OF	-	Offset Filtering
PBRS	-	Pseudo Bit Random Sequence
SBS	-	Stimulated Brillouin Scattering
SRS	-	Stimulated Raman Scattering
SOA	-	Semiconductor Optical Amplifier
SPM	-	Self-Phase Modulation
VOA	-	Variable Optical Attenuator
XPM	-	Cross phase Modulation

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CHAPTER 1

INTRODUCTION

1.1 Fundamental of Optical Communication Systems

Optical communication system different from other communication systems in term of the frequency range of the carrier used to carry the information. The optical carrier frequency typically 100 THz, compared to the microwave carrier frequency of 1 to 10 GHz [1]. Figure 1.1 shows a general block diagram of an optical communication system. It consists of an optical transmitter, communication channel and optical receiver. Optical communication systems can be classified into two categories which are guided and unguided. In guided light wave systems, the optical beam emitted by the transmitter remains spatially confined and this is achieved by using optical fiber [1].

While, unguided optical communication systems, the optical beam emitted by the transmitter spreads in space in a similar manner to radio wave. However, unguided optical systems are less suitable in broadcasting applications than microwave systems because optical beam spreads mainly in the forward direction. In general, the purpose of optical communication will transfer information from one point to another point [2]. The telecommunication application can be widely classified into two categories which are long-haul and short-haul. Long-haul communication systems need high-capacity trunk lines and benefit most from the use of fiber optic light wave system while short-haul telecommunication applications cover intercity and local loop traffic [1]. Such systems normally operate at low bit rates over any distances that is less than 10 km [2].

Figure 1.1: A general block diagram of an optical communication system [2]

1.2 All-Optical Signal Regeneration

Optical transmission is the greatest way to transmit high capacity information in a long-haul transmission systems. The growth of transmission speed and capacity encouraged through the advanced development of optical transmission technologies. The signal degradation becomes more dominant as the optical transmission system moves to higher bit rates and more advanced technologies have evolved since then. All-optical signal regeneration is appropriate to various modulation formats and can work in an ultrafast manner. 2R stands for reamplifying and reshaping the signal while 3R adds retiming of the signal [3]. 2R and 3R regeneration systems can enhance the degraded signals and improve the transmission performance.

The nonlinear properties can be obtained by injecting a sufficiently high light intensity inside the materials, such as fiber [4-5], semiconductor [6-7], and silicon [8-9]. Silica-based highly nonlinear fiber (HNLF), which has a long communication length and high confinement in the waveguide structure, is an attractive nonlinear medium for high bit rate all-optical signal processing [10]. For fiber-based signal regeneration, there are many types of nonlinear effects that can be used which are self-phase modulation (SPM) [10-13], cross-phase modulation (XPM) [14-15], four-wave mixing (FWM) [16-17], and stimulated Raman scattering (SRS) [18]. Detailed discussions on these nonlinearities and their abilities for signal regeneration are discussed in Chapter 2.

This thesis is focused on all-optical 2R regeneration. All-optical 2R regeneration reamplifying and reshaping can improve the degraded signals resulting from fiber loss, dispersion, nonlinearity, and Amplified Spontaneous Emission (ASE) noise [19-21]. Moreover, 2R regeneration is a key technique in minimizing impairments and attaining long-haul transmission distance, scalability and flexibility [22-23]. Figure 1.2 shows the schematic operation of an optical 2R regeneration. It comprises of a transmitter, degradation and regeneration stages.

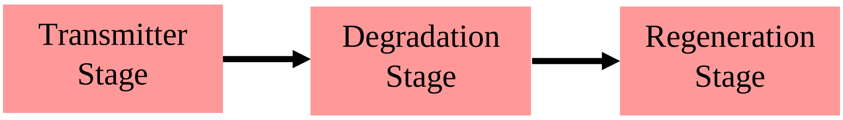

Figure 1.2: Schematic diagram of an optical 2R regeneration [9]

1.3 Problem Statement

Nowadays, the regeneration of all-optical signal must be compatible with the technology of data transmission. Some of the issues in optical transmission systems are signal distortion and fiber losses especially when the signal is transmitted by long-haul transmission system. In addition, the signal is attenuated during transmission because of the inherent properties of optical fiber which will cause considerable reduction of the signal power in the receiver. In addition, signal performance in terms of maximum Q-factor, minimum bit error rate (BER) and bit error rate pattern are poor. As a solution, 2R regenerator (reamplifying, and reshaping) is proposed because it can directly handle degraded signals resulting from fiber loss and distortion. Besides that, the 2R regenerator preserves quality of the signal and allows long-haul transmission system. There are several stages which need to be fulfilled in order to develop the 2R regenerator.

1.4 Objectives

The major objective of this work is to improve the performance of degraded signals resulting from fiber losses and distortion. Specific objectives are as follows:

1. To develop and optimize optical 2R Regeneration based on self-phase modulation.
2. To evaluate the performance of the signal in terms of the maximum Q-factor, minimum bit error rate and bit error rate pattern in All-Optical 2R Regeneration.

1.5 Scope

The scope of this work are:

1. Develop an optical 2R Regeneration by using Optisystem 12.0 software.
2. Regenerate 10 Gbit/s signal by using all-optical regeneration in a single channel both of NRZ-OOK and RZ-OOK moulation format.
3. Regeneration is based on a self-phase modulation.

1.6 Thesis Outline

This thesis contains five chapters. In Chapter 1, the introduction of this thesis is presented. This is followed by literature review in Chapter 2. Chapter 3, discusses the methodology that is used in the development of 2R regeneration in optical communication. The simulation results are shown and analysed in Chapter 4. Finally, Chapter 5 concludes this thesis and discusses the main issues in the regeneration scheme with suggestions for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

2R regeneration is the key technique for minimizing impairments and attaining long-haul transmission distance, scalability and flexibility. This chapter presents the theoretical background of all-optical 2R Regeneration that includes optical transmitter, optical receiver, NRZ signal modulation, RZ signal modulation and nonlinear effects. There are many types of nonlinear effects that can be used in fiber-based signal regeneration, such as self-phase modulation (SPM) [10-13], cross phase modulation (XPM) [14-15], four wave mixing (FWM) [16-17], stimulated Raman scattering (SRS) [18] and stimulated Brillouin scattering (SBS) [24].

2.2 Optical Transmitter

The role of an optical transmitter is to transform an electrical signal into optical form and launch the resulting optical signal into the optical fiber. Figure 2.1 shows the block diagram of an optical transmitter. An optical transmitter consists of an optical source, modulator, and optical output. Semiconductor lasers are used in optical source because of their compatibility with the optical-fiber communication channel. The optical signal is produced by modulating the optical carrier wave. Although an external modulator is used in certain cases, it can be omitted in most cases since the output of a semiconductor optical source can be modulated directly by varying the injection current [1-2].

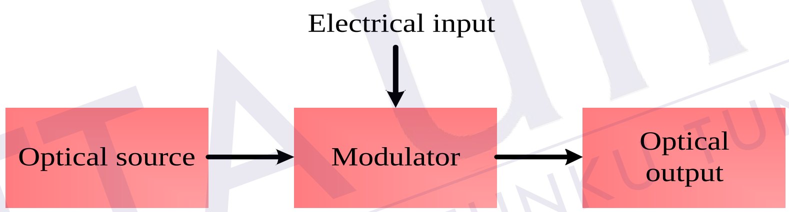

Figure 2.1: Block diagram of an optical transmitter [2]

2.3 Optical Receiver

An optical receiver transforms the optical signal received at the output end of the optical fiber back into the original electrical signal. Figure 2.2 shows the block diagram of an optical receiver. It consists of photodetector and demodulator. Semiconductor photodiodes are used as photodetectors because of their compatibility with the entire system. The design of the demodulator relies on the modulation format used by the lightwave system [1-2].

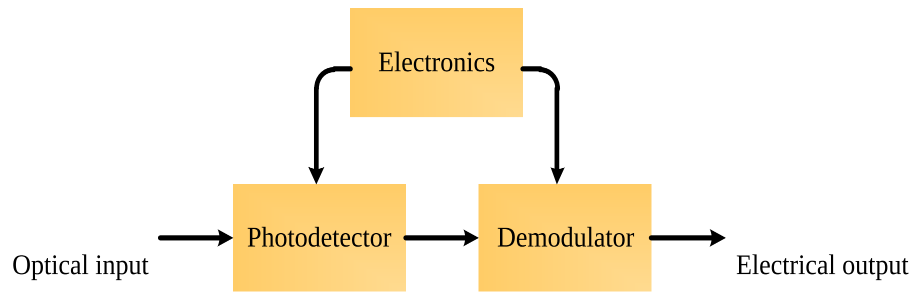

Figure 2.2: Block diagram of an optical receiver [2]

2.4 Modulation Format

There have been a number of optical modulation format in optical communication systems which are binary signalling, non-return-to-zero (NRZ), return-to-zero and phase-shift keying (PSK). The modulation format involved in this thesis are NRZ-OOK and RZ-OOK.

2.4.1 NRZ Format and RZ Format

The unipolar non-return-to-zero (NRZ) code is the easier method for encoding data. Unipolar means that a logic '1' is represented by a light pulse that fills an entire bit period, whereas, for a logic '0', no pulse is transmitted as shown in Figure 2.3. From the figure, the RZ code has an amplitude transition at the beginning of each bit interval when a binary '1' is transmitted and no transition when a binary '0' is transmitted [24].

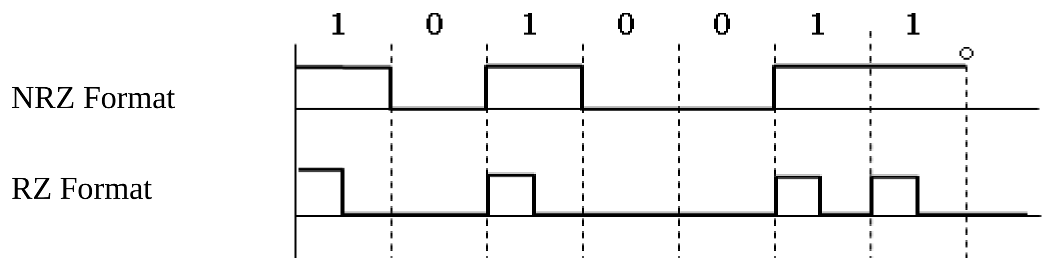

Figure 2.3: NRZ and RZ code pattern [24]

2.5 Nonlinear-Optical Effect

Optical nonlinearities can be categorised into two general categories. The first category is nonlinear inelastic scattering processes which are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) [24]. The second category of nonlinear effects arises from the intensity-dependent variations in the refractive index of a silica fiber, which is known as the Kerr effect that includes self-phase modulation (SPM) [10-13], four-wave mixing (FWM) [16-17] and cross-phase modulation (XPM) [14-15, 24]. Figure 2.4 illustrates the classification of optical nonlinearities.

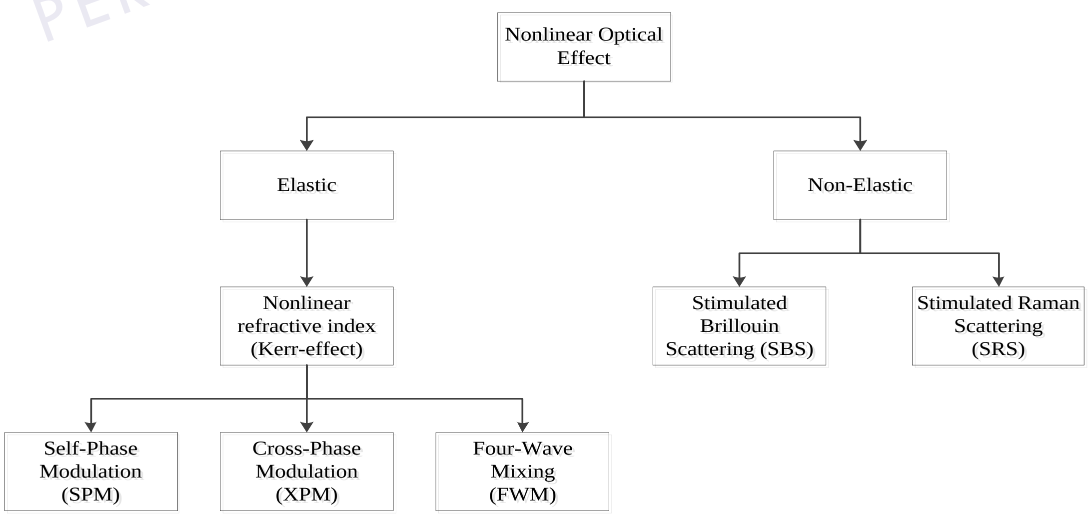

Figure 2.4: Classification of optical nonlinearities [25]

2.5.1 Self-Phase Modulation (SPM)

The refractive index, *n* of many optical materials has a weak dependence on optical intensity, *I* and is given by:

$$n(I) = n_0 + n_2 I \qquad (2.1)$$

where n_0 is the ordinary refractive index of the material, n_2 is the nonlinear index coefficient and *I* is the intensity of the pulse.

The Kerr nonlinearity is known as the nonlinearity in the refractive index [2]. It gives upsurge to self-phase modulation (SPM), which converts optical power fluctuations in the same wave in single-wavelength links. [26-29]. Main parameter is the nonlinear coefficient, Υ which shows the magnitude of the nonlinear effect for SPM. This parameter is given by:

$$\Upsilon = \frac{2\pi}{\lambda}\frac{\eta_2}{A_{eff}} \qquad (2.2)$$

where λ is a free space wavelength and A_{eff} is an effective core area.

Figure 2.5 shows the effect inside the SPM. From the figure, the time axis is normalized to the parameter, t_0 which is the pulse half-width at the 1/*e*-intensity point. The edges of the pulse represent time-varying intensity, which rises quickly from zero to maximum value and then returns to zero. A time-varying signal intensity will produce a time-varying refractive index in a medium with an intensity-dependent refractive index. Therefore, the index at the peak of the pulse will be slightly distinct than the value in the wings of the pulse. The leading edge will observe a positive dn/dt, whereas the trailing edge will observe a negative dn/dt. The temporally varying index change results in a temporally varying phase change as shown in Figure 2.5. The consequence is that the instantaneous optical frequency differs from its initial value v_0 across the pulse. Different parts of the pulse undergo different phase shifts since phase fluctuations are intensity-dependent. It is called frequency chirping. SPM effects are more noticeable for higher-intensity pulses since the degree of chirping depends on the transmitted power.

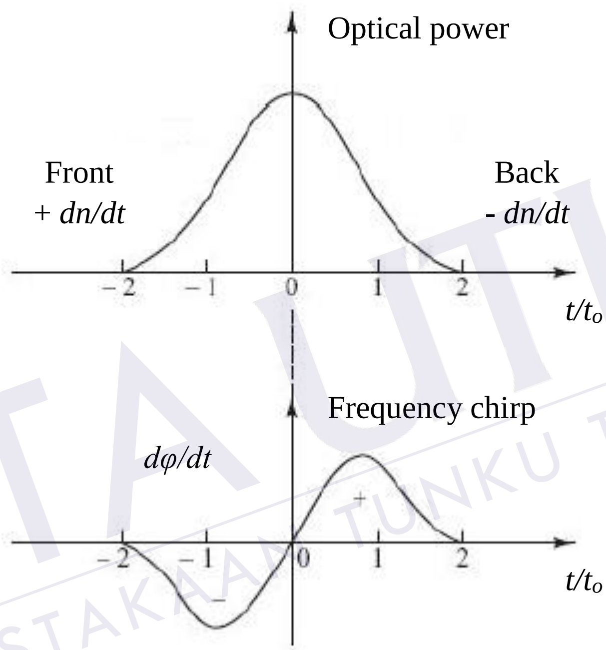

Figure 2.5: Explanation of spectral broadening of a pulse due to self-phase modulation [27]

2.5.2 Cross-Phase Modulation (XPM)

Cross-phase modulation (XPM) is identical to SPM, except that two overlapping but distinguishable pulses (different frequencies or polarizations) are involved [24]. One pulse will modulate the index of the medium, which then leads to the phase modulation of an overlapping pulse. Thus, if phase encoding is employed or if intensity modulation is used

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