UNIVERSITI PUTRA MALAYSIA

PROPAGATION CHARACTERISTICS OF FEMTOSECOND SOLITON AND DEVELOPMENT OF WAVELENGTH CONVERTER AND ANALOG-TO-DIGITAL CONVERTER MODEL

AIDA ESMAEILIAN-MARNANI

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PROPAGATION CHARACTERISTICS OF FEMTOSECOND SOLITON
AND DEVELOPMENT OF WAVELENGTH CONVERTER AND ANALOG-TO-DIGITAL CONVERTER MODEL

By

AIDA ESMAEILIAN-MARNANI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2012
DEDICATION

This thesis is dedicated to

who created me

and

he guides me
Research interests on femtosecond solitons have increased along with upgrading in ultrafast optics. Moreover, all-optical devices have been developed based on ultrashort solitons.

Despite the wide attraction of femtosecond solitons, which lies in providing high resolution, high intensity, and high bandwidth, attempt in this realm is associated with more complexity and more problems due to manifestation of higher order linear and nonlinear effects. To get around these obstacles, many researches have been conducted during the last decades in both, reducing the destructive effects on pulse propagation and developing optimal devices based on ultrashort solitons.

This dissertation investigates the potential of overlapping 50 femtosecond soliton in improving the propagation characteristics as a low power ultrafast pulse over standard single-mode fiber (SSMF). Pulse stream propagation is also explored.
Moreover, realization of two all-optical devices, ultrafast wavelength conversion, and two-bit analog-to-digital conversion, are investigated for ultrashort solitons.

First, improving the 50 femtosecond pulse propagation is realized by substituting input pulse with a reduced-order overlapping soliton pair. This approach decreases the pulse time delay compared to fundamental soliton and increases the pulse stability compared to reduced-order soliton. In the pulse stream, in addition to using overlapping soliton pair, perturbation is also applied to the fiber by step change in the second order dispersion to avoid pulses from collision.

Second, survey on the realization of wavelength conversion, which is based on second-order 50 femtosecond dark solitons with hyperbolic secant pulse, is accomplished by introducing localized dispersion perturbation along the optical fiber. It is shown that the realization of 1×2 channel wavelength converter for femtosecond pulses is possible.

Ultimately, realization of two-bit all-optical analog-to-digital conversion is explored for analog signal sampled by a 50 femtosecond soliton sequence. Two methods are exploited. The first one is based on filtering the broadened soliton spectrum after evolution over half of the soliton period. In the second one, pulse is temporally sampled at the specified times after propagating through one soliton period. The utilized methods in this research have fast response and relatively simple design in comparison to the existing solutions.
Consequently, the main contributions include research for improving femtosecond pulse and pulse stream propagation over short fiber lengths, realization of all-optical wavelength conversion for dark soliton with hyperbolic secant pulse, and two-bit all-optical analog to digital conversion for femtosecond soliton.
Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PROPAGATION CHARACTERISTICS OF FEMTOSECOND SOLITON AND DEVELOPMENT OF WAVELENGTH CONVERTER AND ANALOG-TO-DIGITAL CONVERTER MODEL

Oleh

AIDA ESMAEILIAN-MARNANI

Mac 2012

Pengerusi: Ahmad Fauzi Abas, PhD

Fakulti: Kejuruteraan

Minat kajian pada soliton femto-saat telah berkembang bersama dengan peningkatan taraf dalam optik ultra pantas. Tambah pula, semua alat optik telah dibangunkan berasaskan soliton ultra pendek.

Walaupun tarikan luas pada soliton femto-saat, yang merangkumi dalam menyediakan peleraian yang tinggi, kecerahan yang tinggi, dan lebar jalur tinggi, percubaan dalam alam ini dikaitkan dengan lebih banyak kerumitan dan lebih banyak masalah disebabkan manifestasi linear peringkat lebih tinggi dan kesan-kesan tak linear. Untuk membiasakan sekitar halangan-halangan ini, kebanyakan penyelidikan telah dijalankan semasa dekad terakhir dalam kedua-dua, mengurangkan kesan-kesan yang memusnahkan pada pembiakan denyut dan membangunkan alat-alat optimum berdasarkan kepada soliton ultra pantas.

Pertama, meningkatkan 50 femto-saat pembiakan denyut disedari dengan menggantikan memasukkan denyut dengan satu perintah terkurang bertindih soliton sepasang. Pendekatan ini mengurangkan tunda masa denyut berbanding dengan soliton asas dan meningkatkan kestabilan denyut berbanding dengan soliton perintah terkurang. Dalam aliran denyut, tambahan kepada menggunakan soliton bertindih sepasang, usikan juga digunakan ke atas serat oleh tukar langkah dalam penyerakan peringkat kedua untuk mengelak dari pelanggaran denyut-denyut.

Kedua, meninjau pada kesedaran penukaran panjang gelombang, yang berdasarkan kepada 50 femto-saat peringkat kedua soliton gelap dengan denyut sekan hiperbolaan, dicapai dengan memperkenalkan usikan penyerakan setempat sepanjang gentian optik. Ia menunjukkan kesedaran bagi 1×2 saluran penukar panjang gelombang untuk denyut femto-saat adalah mungkin.

Akhirnya, kesedaran dua bit sepenuh optik penukaran analog kepada digital dijelajahi untuk isyarat analog dirasai oleh jujukan soliton 50 femto-saat. Dua cara telah dieksploitasi. Pertama adalah berdasarkan menapis spektrum soliton yang telah melebar selepas evolusi ke atas separuh daripada tempoh soliton. Yang kedua,
denyut bermasa menyampel di masa-masa yang ditetapkan selepas membiak melalui satu tempoh soliton. Kaedah-kaedah yang telah digunakan dalam penyelidikan ini mempunyai reaksi pantas dan reka bentuk yang agak mudah dalam perbandingan bagi penyelesaian sedia ada.

Akibatnya, sumbangan-sumbangan utama termasuk penyelidikan untuk meningkatkan denyut femto-saat dan pelepasan aliran denyut ke atas panjang gentian pendek, kesedaran semua penukaran panjang gelombang optik untuk soliton gelap dengan denyut sekan hiperbolaan, dan dua bit sepuh optik untuk penukaran analog kepada digital untuk soliton femto-saat.
ACKNOWLEDGEMENTS

In Quran, surat 27, ayat 40, it is said “This is by the grace of my Lord that he may test me whether I am grateful or I am thankless”. Then, my main appreciation is to Allah that kindly helps me every time and everywhere.

I would like to thank my compassionate supervisor, Dr. Ahmad Fauzi Abas, for his overall support, guidance, and patience all these years.

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I would like to express my deepest gratitude to my beloved husband, Amir Hossein Zaeri, for his endless support during ten years studying beside him. I also wish to thank my beloved mother for her unconditional support and love. I truly appreciate her concern and her pray for me. I also dedicate this thesis to my darling son, Mohammad Hossein, who has already stepped into this marvellous world.
I certify that an Examination Committee has met on 9 March 2012 to conduct the final examination of Aida Esmailian-Marnani on her Doctor of Philosophy thesis entitled "Propagation Characteristics of Femtosecond Soliton and Development of Wavelength Converter and Analog-to-Digital Converter Model" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the student be awarded the Doctor of Philosophy.

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Date:
DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

AIDA ESMAEILIAN-MARNANI

Date: 9 March 2012
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<tr>
<td>ADC</td>
<td>Analog-to-Digital Convertor</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analog Convertor</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion Compensating Fiber</td>
</tr>
<tr>
<td>DMF</td>
<td>Dispersion Managed Fiber</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
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<td>FWM</td>
<td>Four-Wave Mixing</td>
</tr>
<tr>
<td>GVD</td>
<td>Group-Velocity Dispersion</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach-Zehnder Interferometer</td>
</tr>
<tr>
<td>NOLM</td>
<td>Nonlinear Optical Loop Mirror</td>
</tr>
<tr>
<td>NLSE</td>
<td>Nonlinear Schrödinger Equation</td>
</tr>
<tr>
<td>SBS</td>
<td>Stimulated Brillouin Scattering</td>
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<td>SSMF</td>
<td>Standard Single-Mode Fiber</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon-On-Insulator</td>
</tr>
<tr>
<td>SPM</td>
<td>Self-Phase Modulation</td>
</tr>
<tr>
<td>SRS</td>
<td>Stimulated Raman Scattering</td>
</tr>
<tr>
<td>SSFM</td>
<td>Split-Step Fourier Method</td>
</tr>
<tr>
<td>TOD</td>
<td>Third-Order Dispersion</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>XGM</td>
<td>Cross-Gain Modulation</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross-Phase Modulation</td>
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</tbody>
</table>
LIST OF SYMBOLS

\( \alpha \)  
Attenuation constant

\( \beta_2 \)  
GVD parameter

\( \beta_3 \)  
Third-order dispersion

\( \gamma \)  
Nonlinear coefficient

\( \lambda_0 \)  
Carrier wavelength

\( \lambda_D \)  
Zero-dispersion wavelength

\( \nu_0 \)  
Carrier frequency

\( A_{\text{eff}} \)  
Effective core area

\( c \)  
Light velocity in free space

\( n_2 \)  
Second-order nonlinear refractive index

\( N \)  
Soliton order

\( P_0 \)  
Initial peak power

\( T_R \)  
Raman time constant

\( U \)  
Normalized pulse amplitude

\( Z_0 \)  
Soliton period
CHAPTER 1
INTRODUCTION

1.1 Background

In the last decades, numerous advances in ultrafast technologies have motivated many researchers to explore about optical femtosecond pulses due to their eminent characteristics.

Ultrashort pulses have found substantial applications in diverse areas. There is a demand for shorter pulses in tracing chemical and physical phenomena because of providing high resolution. Ultrafast spectroscopy and femto-chemistry are through this purpose [1-3]. In addition, there is also a demand for short pulses in bioimaging. Moreover, the high intensity associated with ultrashort pulses has created some applications in surgery, x-ray generation, and particle acceleration in physics [4-7]. In addition to previous applications, ultrashort pulses have led to the development of wavelength division multiplexing (WDM) optical communications, as pulses with short duration occupy high bandwidth [8-9]. Accordingly, faster data transmission has been realized. Moreover, all-optical devices are being developed for ultrashort pulses toward becoming adapted to ultrafast communications. During the last few decades, various kinds of all-optical logic gates, switches, delay lines, multiplexers, wavelength converters, analog-to-digital converters (ADCs), digital-to-analog converters (DACs), and many other devices have been reported to be developed [10-13].
All these applications and prominent advantages do not fade the problems associated with employing femtosecond pulses. The higher intensity and peak power of ultrashort pulses may lead to pulse distortion along the fiber. This distortion, which sometimes limits the extension of applications, may include pulse deformation, time deviation, and pulse broadening. In addition to pulse distortion, the complexity of methods analysing the ultrashort pulses is another considerable issue, because, the higher order effects and asymmetric propagation of pulses should be considered in these approaches.

Optical soliton is a kind of pulse envelope, which has been able to overcome some impairment. Soliton is formed due to the interplay between group-velocity dispersion (GVD) and self-phase modulation (SPM), both of them individually distort the optical pulse propagation. It is typically known by hyperbolic-secant pulse. However, other types of solitons including dark solitons, dispersion-managed solitons, and bistable solitons have also been introduced.

Soliton can propagate undistorted over long distances in a lossless fiber. This is the outstanding characteristic of soliton over square pulse. Therefore, hyperbolic secant pulse has extensively been substituted for conventional pulse in many applications. In particular, ultrashort solitons have been utilized in a wide range of applications in ultrafast optics. In spite of better characteristics of ultrashort soliton compared to ultrashort square pulse, there are still difficulties with higher order effects and other destructive effects. Therefore, systems operating based on femtosecond solitons are to confront with different problems, including timing jitter, soliton collision, noise, and pulse deformation. To deal with these impairments, various kinds of methods
provided by fibers or other devices have been reported [14-17]. For example, dispersion managed fibers (DMFs), dispersion compensating fibers (DCFs), fibers with different dispersion profiles, fiber gratings, nonlinear optical loop mirror (NOLM), liquid crystal modulators, dark solitons, and phase conjunction are proposed. However, there are still demands for methods to overcome destructive effects in the ultrafast field.

High resolution, fast sampling, and optical computing applications may deal with one important obstacle due to time delay and dispensable high power of ultrashort pulses. Solving this problem can lead to extension of related applications.

Ultrashort solitons have contributed to realization of ultrafast optical devices. During the last decades, there has been an advanced development in optical devices design based on solitons. For example, ultrafast optical delay line based on soliton characteristics [12, 18], all-optical soliton switching [19-20], and all-optical analog-to-digital converters [21-22] have been reported. Wavelength conversion has also attracted some researchers to study about [23-24]. Two all-optical devices, namely wavelength converter and ADC, are the focus of this dissertation.

Wavelength converter, which changes the wavelength of the incoming signal, is a critical component in optical networks. It is used to adapt the input wavelength to the network bandwidth, to improve the utilization of wavelength within the network, or to adapt outcoming signal from one sub-network into a suitable one to be utilized in another sub-network. In order to realize optical wavelength conversion, different approaches involving optoelectronic, optical gating, wave-mixing, and
All-optical techniques yield devices with less power consumption and faster response, although they are more complex compared to the electrical methods and they may confront problems such as transparency to different modulation formats and noise. In ultrafast applications, performance speed is an important factor. However, ultrafast wavelength conversions for femtosecond pulses have been rarely reported [11, 25, 28]. These few reports are commonly performed by using waveguides. Exploration towards finding economical and simple methods for realizing all-optical devices for femtosecond pulses is still one of the major challenges in ultrafast optics.

Tremendous development in digital signal processing, despite analog nature of many signals, has been the motivation of vast research into the ADCs. ADC holds critical role in data acquisition and processing systems. In ultrafast optics, high-speed and high-resolution ADC is an essential component. All-optical design based on ultrashort pulses helps to the realization of such an ADC. Most proposed methods uses Mach-Zehnder interferometer (MZI) or nonlinear optical loop mirror (NOLM) [29-30]. On the other hand, some methods are limited to only two bits [21, 31-32]. Vast researches are still directed into realization of ultrafast ADC, because the current developments are not fast enough in compare to the huge progress in ultrafast communication.

Consequently, the significant role of ultrashort solitons in ultrafast optics and insatiable demand for ultrafast devices in this field, are the motivation of this dissertation, which explores three issues that are based on femtosecond solitons. First, the possibility of reducing propagation time delay of low power ultrashort
pulse and pulse stream by using overlapping soliton pair is studied. Second, wavelength conversion with hyperbolic secant femtosecond pulse in normal dispersion regime is studied. Finally, realization of two-bit ADC by using two different methods in standard single-mode fiber (SSMF) is thoroughly explored. It is expected that the findings from our study will contribute towards progress in ultrafast optics research and industry.

1.2 Problem statement

Fundamental soliton has prominent characteristics compared to square pulse. However, in ultrafast applications where high resolution and/or ultrashort pulse width is important, such as optical computing and signal processing [33-34], high peak power of femtosecond soliton is power wasting and even destructive. Moreover, soliton with lower power rapidly disperses through the fiber. Although many solutions are reported to mitigate pulse destructions by using external devices, improving laser sources, and different kinds of fibers, to our knowledge the potential of inherent characteristics of pulse to show better performance in ultrafast low power applications are not considered.

All-optical fast wavelength conversion has been an important issue for many researches. However, it is seldom reported for femtosecond pulses due to problems associated with ultrashort pulses [11, 25, 28, 35]. These few researches are reported at least for 300 fs pulse. Moreover, they have usually utilized waveguides, such as silicon-on-insulator (SOI) and LiNbO₃, in addition to some external devices, such as filter and optical polarization controller. Exploring to find simple and economical
approaches continues. It is predicted that methods using a few devices are less imposed by noise and are more suitable for femtosecond based wavelength conversion. Lee et al. in [23] and [36], investigated the possibility of realizing wavelength conversion by using higher-order soliton broadened spectrum, which undergoes three different forms of localized channel perturbation. One of the utilized perturbations is step increase in dispersion. It is almost a simple method without using costly and complicated devices. This method has also been exploited by Ebnali et al. published in 2007 [24]. They have presented a multichannel wavelength conversion for higher order solitons. Both researches consider picosecond solitons without being affected by dominant higher order nonlinear effects, which is a serious ignorance for femtosecond solitons.

Various methods for realization of fast optical ADCs have been developed in recent decades. Quantization is one important stage in ADCs. This is usually implemented based on Kerr effect which has ultrafast response. However, reported techniques suffer from many problems such as need for high-power femtosecond pulses to raise the nonlinear phenomena [37-38] or polarization sensitivity [39-40]. Moreover, to our knowledge, ultrafast ADCs are reported at least for 500 fs as published in [41]. Demand for ultrafast ADCs is increasing while complicated methods using many devices, impose noise and disallow use of sampled pulse with a few femtosecond pulse width. It is predicted that simple methods with limited devices can contribute to realization of ultrafast ADCs based on a few femtosecond sampled pulse. Oda in [21] has proposed a two-bit all-optical ADC, where analog pulse is sampled by a picosecond soliton sequence. His scheme is based on filtering symmetrically broadened and split spectrum induced by self-phase modulation (SPM) or soliton
effect. The output is a two-bit Gray code. This method is almost simple without using costly and complicated devices in comparison to other competing solutions.

1.3 Objectives

The objectives of this research are:

1. To study the potential of overlapping soliton pair in improving the propagation characteristics over SSMF.

2. To study the possibility of realizing all-optical wavelength conversion for femtosecond pulses.

3. To study the possibility of realizing quantization in two-bit all-optical analog-to-digital conversion for femtosecond solitons.

1.4 Scope of work

This research involves modelling work, mathematical analysis and simulations. The main focus is to study the propagation of overlapping femtosecond soliton pair over short SSMF. The same study will also be conducted by using the soliton stream. This thesis will also study the potential uses or applications of femtosecond soliton.
The overall stages are summarized in Figure 1.1. The scope of work for propagation characteristics of overlapping soliton pair, all-optical wavelength conversion, and quantization in ADC are shown in Figure 1.2 and Figure 1.3.

Figure 1.1. Overall methodology
Overlapping soliton pair

Introducing overlapping soliton pair with different $N$s and $q_0$s, but with equal time duration as that of 50 fs fundamental soliton

Simulating overlapping soliton pair propagation through SSMF

Comparing with fundamental soliton

Comparing the overlapping soliton pairs in curves

Comparing pulse streams with different perturbation positions with 50 fs fundamental soliton stream

Finding the best perturbation position

Comparing pulse stream under best perturbation with 50 fs fundamental soliton stream

Applying perturbation if pulses collide

Comparing with reduced-order soliton with the same amplitude

Finding the best perturbation step for each soliton pair

Figure 1.2. Methodology stages to achieve suitable low power ultrashort pulse by using overlapping soliton pair
Figure 1.3. Methodology stages to realize (a) optical wavelength conversion, (b) optical quantization for analog-to-digital conversion
1.5 Thesis overview

This thesis is organized in five chapters, which are commonly explained based on three objectives of this research, separately. The current chapter provided an introduction to the main issues dealing with this thesis. Problem statement and the main objectives are also clarified.

Chapter 2 is devoted to literature review. In this chapter, the basic concepts of this research are explained. Moreover, different methods related to our dissertation are introduced and criticized in different sections.

Chapter 3 explains the utilized methods. First, the methodologies, which are common through achieving different objectives, are introduced. Next, the methodology related to each objective is explained, separately. More details about utilized methods are clarified in Chapter 4.

Chapter 4 classifies the achieved results in three sections. First, characteristics of femtosecond pulse realized by using reduced-order overlapping soliton pair over short SSMF is explained for single pulse and pulse stream. Next, realization of all-optical wavelength conversion for femtosecond secant hyperbolic pulse is elaborated. Finally, realization of two-bit all-optical analog-to-digital conversion for femtosecond soliton is discussed based on two different methods.

Ultimately, Chapter 5 concludes this dissertation based on our three objectives and suggests possible areas on the future work.
REFERENCES


[52] J. S. Malhotra and M. Kumar, "Performance analysis of NRZ, RZ, CRZ and CSRZ data formats in 10 Gb/s optical soliton transmission link under the impact of


