UNIVERSITI PUTRA MALAYSIA

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

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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

Abstract of thesis presented to the Senate of University Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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March 2012

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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

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Minat kajian pada soliton femto-saat telah berkembang bersama dengan penaikan taraf dalam optik ultra pantas. Tambahan 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.

Disertasi ini menyiasat potensi pertindihan bagi 50 femto-saat soliton dalam meningkatkan ciri-ciri pembiakan sebagai denyut ultra pantas kuasa rendah ke atas standard gentian mod tunggal (SSMF). Pembiakan aliran denyut juga telah dijelajahi. Tambahan pula, kesedaran bagi dua semua alat optik, penukaran panjang gelombang ultra pantas dan dua bit penukaran analog kepada digital, adalah disiasat untuk 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 dieksploitasikan. 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 pembiakan aliran denyut ke atas panjang gentian pendek, kesedaran semua penukaran panjang gelombang optik untuk soliton gelap dengan denyut sekan hiperbolaan, dan dua bit sepenuh optik untuk penukaran analog kepada digital untuk soliton femto-saat.

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I certify that an Examination Committee has met on **9 March 2012** to conduct the final examination of Aida Esmaeilian-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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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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LIST OF ABBREVIATIONS

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

LIST OF SYMBOLS

α	Attenuation constant
β_2	GVD parameter
β_3	Third-order dispersion
γ	Nonlinear coefficient
λ_0	Carrier wavelength
λ_D	Zero-dispersion wavelength
v_0	Carrier frequency
A_{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 bi-stable 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 interferometric techniques have been reported [25-27]. 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 $LiNbO_3$, 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.

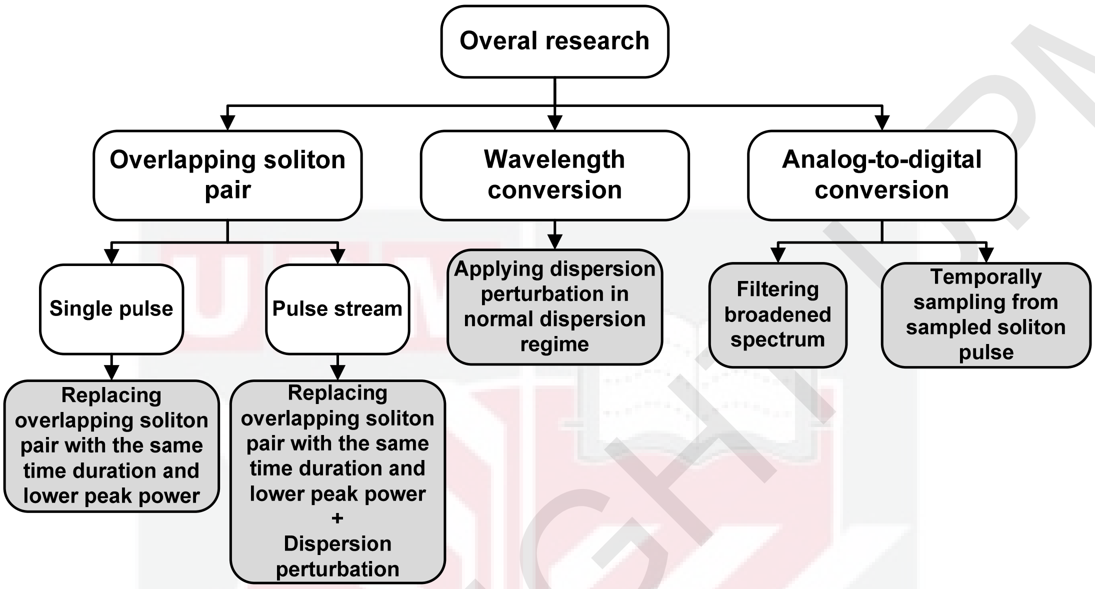

Figure 1.1. Overall methodology

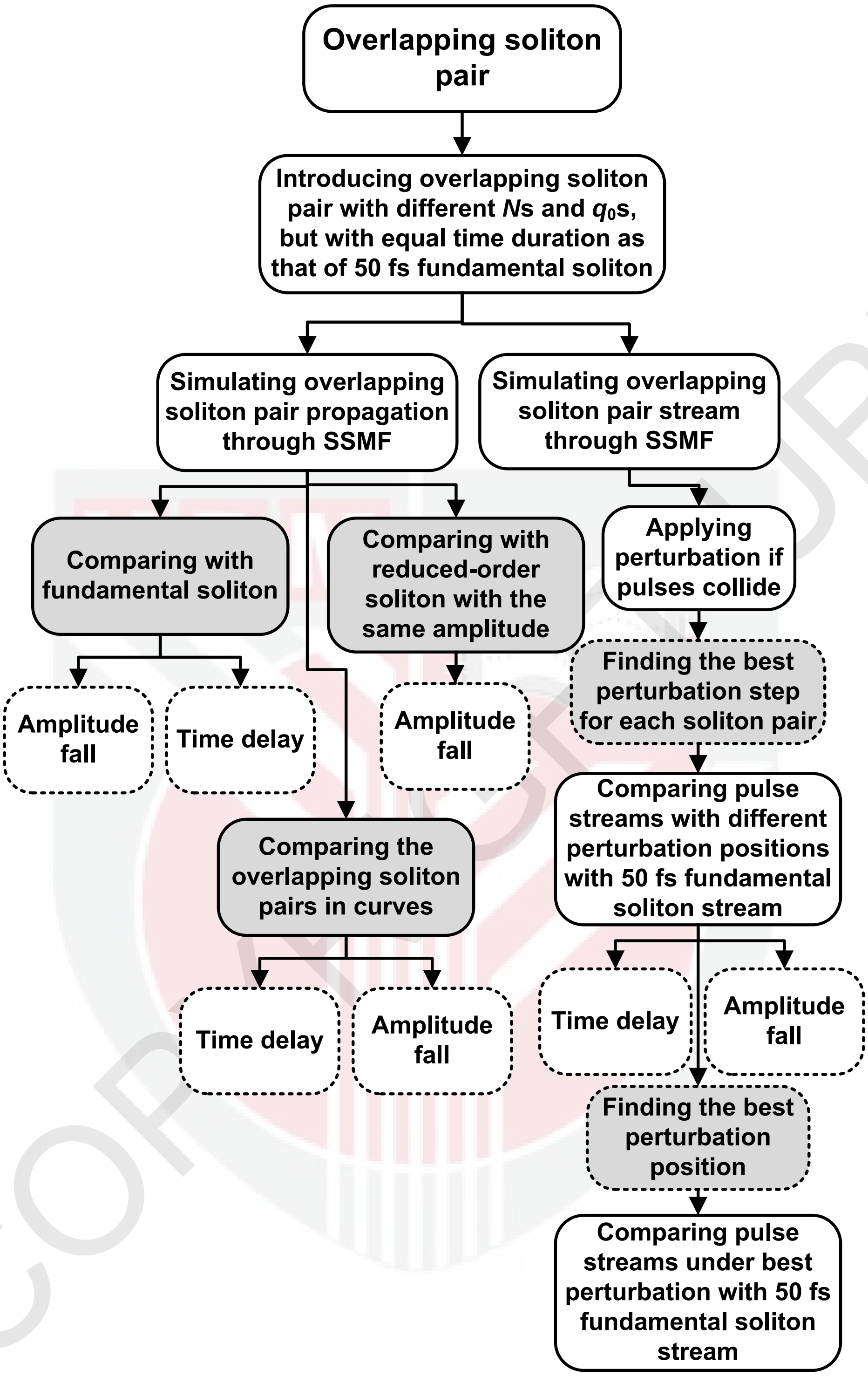

Figure 1.2. Methodology stages to achieve suitable low power ultrashort pulse by using overlapping soliton pair

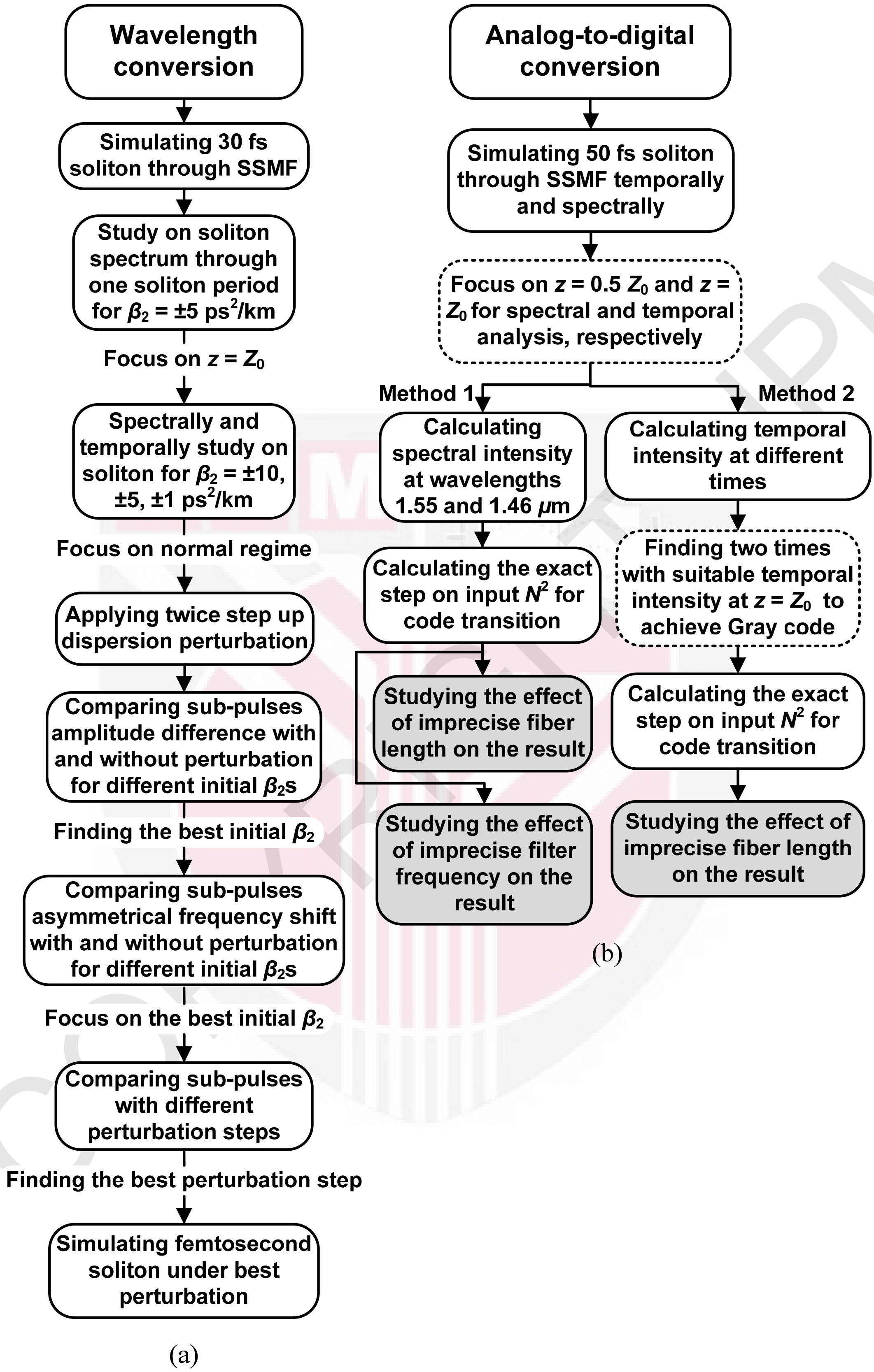

Figure 1.3. Methodology stages to realize (a) optical wavelength conversion, (b) optical quantization for analog-to-digital conversion

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.

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