OPTICAL BISTABILITY IN MOBIUS MICRORING RESONATOR

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Dedicated with my deepest love and affection to
my family
For their supports and blessings

To all my friends specially Nurul Faridah
For their motivational support

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ABSTRACT

Optical bistability is one of the nonlinear properties that produce an essential light control which contributes in various photonics applications such as all-optical switching and optical memory. In this thesis, bistability behavior of optical signals generated in microring resonator (MRR) systems using bright soliton input pulses with 1.55 μm wavelength is studied. The generation of the bistable signals is mathematically analyzed through the transfer matrix analysis and simulated by the MATLAB software version 2014a. The behavior of the propagated input pulses in terms of intensity and phase shift is investigated for different configurations including All-pass MRR, Add-drop MRR and PANDA MRR systems. Three novel Mobius MRR configurations consist of All-pass Mobius MRR, Add-drop Mobius MRR and PANDA Mobius MRR configurations are proposed and the light treatment through Mobius MRR systems is analytically studied and compared with conventional MRR systems. For determining the effect of physical parameters such as ring radius, control power variation and coupling coefficients on the output pulse, the optical hysteresis loops of bistable signals are generated via silicon-on-insulator nonlinear MRR configurations. The analyses of the results are conducted by calculating the output switching power, input threshold power and hysteresis width of bistable loop for radius variation from 1 μm to 6 μm with an increment of 1 μm, change of coupling coefficient from 0.4 to 0.9 with increment of 0.1 and variation of controlled power from 50 mW to 100 mW with increment of 10 mW. It is found that small coupling coefficients enhance the hysteresis width and output switching power of optical bistable loops. The value of output switching power obtained at the output port of Add-drop Mobius MRR is 30.26 mW which is higher than those obtained from All-pass Mobius and PANDA Mobius MRR configurations. The threshold powers of the All-pass Mobius, Add-drop Mobius and PANDA Mobius configurations for on switching operations are obtained as 20.59 mW, 31.39 mW and 25.19 mW respectively. It is found that, optimization of the Mobius MRR system can be conducted by increasing the external radius of Mobius ring waveguide and decreasing the coupling coefficient with implementation of the high control power. In this work, the Mobius configurations are introduced as a convenient compact design to generate optical bistability in comparison with conventional configurations of nonlinear MRR system.

ABSTRAK

Optik dwikestabilan adalah salah satu daripada sifat-sifat tak linear yang menghasilkan kawalan cahaya penting yang menyumbang dalam pelbagai kegunaan fotonik seperti semua-pensuisan optik dan memori optik. Dalam tesis ini, tingkah laku dwikestabilan isyarat optik yang dihasilkan dalam sistem pengalun cincin mikro (MRR) menggunakan denyut input soliton cerah dengan panjang gelombang 1.55 μm telah dikaji. Penjanaan isyarat dwistabil dianalisis secara matematik melalui analisis matriks pindahan dan disimulasikan dengan perisian MATLAB versi 2014a. Kelakuan denyut input rambatan dikaji dari segi keamatan dan anjakan fasa untuk susunan yang berbeza termasuk sistem MRR lepasan-semua, MRR penambah-jatuh dan MRR PANDA. Tiga susunan MRR Mobius baru terdiri daripada susunan MRR Mobius lepasan-semua, MRR Mobius penambah-jatuh dan MRR Mobius PANDA dicadangkan dan rawatan cahaya melalui sistem MRR Mobius dikaji secara analitik dan dibandingkan dengan sistem MRR konvensional. Untuk menentukan kesan parameter fizikal seperti perubahan jejari cincin, kuasa kawalan dan pekali gandingan denyut output, gelung histerisis optik isyarat dwistabil telah dihasilkan melalui susunan MRR tak linear silikon-atas-penebat. Analisis keputusan dilakukan dengan pengiraan kuasa pesuisan output, kuasa ambang input dan lebar gelung histerisis dwistabil untuk perubahan jejari daripada 1 μm hingga 6 μm dengan kenaikan 1 μm, perubahan pekali gandingan daripada 0.4 kepada 0.9 dengan kenaikan 0.1 dan perubahan kuasa kawalan daripada 50 mW kepada 100 mW dengan kenaikan 10 mW. Ia didapati bahawa pekali gandingan kecil meningkatkan lebar histerisis dan kuasa pensuisan output gelung optik dwistabil. Nilai kuasa pensuisan output diperolehi di port output MRR Mobius penambah-jatuh ialah 30.26 mW yang mana lebih tinggi daripada susunan MRR Mobius lepasan-semua dan MRR Mobius PANDA. Kuasa ambang susunan Mobius lepasan-semua, Mobius penambah-jatuh dan Mobius PANDA untuk operasi pensuisan terpasang diperoleh masing-masing sebagai 20.59 mW, 31.39 mW dan 25.19 mW. Ia didapati bahawa, pengoptimuman sistem Mobius MRR boleh dilakukan dengan meningkatkan jejari luar pemandu-gelombang cincin Mobius, dan mengurangkan pekali gandingan dengan pelaksanaan kuasa kawalan yang tinggi. Dalam kerja ini, susunan Mobius diperkenalkan sebagai reka bentuk padat yang mudah untuk menjana dwikestabilan optik berbanding dengan susunan konvensional pada sistem MRR tak linear.

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LIST OF ABBREVIATIONS

MRR	-	Microring Resonator
FDTD	-	Finite-Different-Time-Domain
SPR	-	Surface Palsmon Resonance
VCSEL	-	Vertical Cavity Surface Emitting Laser
EDF-FBG	-	Erbium Doped Fiber-Fiber Bragg Grating
FBG	-	Fiber Bragg Grating
SMFPLD	-	Single Mode of Fabry Perot Laser Diode
EIR	-	Induced Reflection Effect
WGM	-	Whispering Gallery Mode
NLC	-	Nematic Liquid Crystal
PHI	-	Photo Induced Isotropic
ICP	-	Inductively Plasma Coupled
SEM	-	Scanning Electron Microscopy
All-pass M	-	All-pass Mobius
Add-drop M	-	Add-drop Mobius
PANDA M	-	PANDA Mobius

LIST OF SYMBOLS

ε_0 - Electric vacuum permittivity
χ - Electric susceptibility
α - Attenuation loss
P - Polarization
P^{NL} - Nonlinear polarization
c - Speed of light
n - Internal refractive index
ω_0 - Angular frequency
E - Electric field
P_o - Nonlinear angular frequency
t - Propagation time
$X^{(i)}$ - i^{th} order of susceptibility
χ_{eff} - Effective susceptibility
n_0 - Linear refractive index
k_0 - Wavenumber
L - Propagation length
I - Intensity
ϕ_L - Linear phase shift
ϕ_{NL} - Nonlinear phase shift
λ - Wavelength
β - Propagation constant
T - Pulse propagation time
v_g - Group velocity
β_2 - Group velocity dispersion parameter
ΔT - Pulse spreading time
L_D - Dispersion length

T_0 - Pulse width
A - Pulse amplitudes
$a(t, z)$ - Pulse envelope
$f(x, y)$ - Spatial structure of optical field
$\beta(\omega)$ - Phase constant
β_{nl} - Nonlinear phase constant
β_l - Linear phase constant
I_o - Pulse propagation time
z - Pulse propagation distance in z direction
L_{NL} - Nonlinear length
η_0 - Wave impedance
I_n - Current amplitude
N - Number of ladder circuit
L' - Inductance
C' - Capacitance
M - Mutual impedance
k - Wavevector
$n_{2'}$ - Waveguide 2 refractive index
n_1 - Waveguide 1 refractive index
μ_o - Vacuum permeability
S_1 - Complex amplitude
u - Wave amplitude function
C_{21} - Coupling coefficient waveguide 1 to 2
iS - Cross coupling parameter
C - Self-coupling parameter
T' - Transmission coefficient
R' - Reflection coefficient
ϕ_{H} - High negative detuning
ϕ_{L} - Low negative detuning
ϕ_0 - Centre detuning
κ_{i} - Coupling coefficient at coupling region *i*
n_2 - Nonlinear index
A_{eff} - Effective area

E_i	-	Electric field at *i* position
E_{im}	-	Electric field at *i* position for Mobius resonator
ξi	-	Phase shift for *i* radius
γ_i	-	Propagation loss at coupling region *i*
A_{eff}	-	Effective area

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Optical bistability is one of the nonlinear properties which has contributed in various applications such as optical transistors [1, 2], optical logic switching [3, 4], optical signal processing [5], fiber communication [6-8] and optical memories [7, 9, 10]. Optical bistability is a hysteresis effect that illustrates two possible output power states within an input power range in a nonlinear optic system. The generation of optical bistability utilized for producing the change of the refractive index of the material with the effect of the input signal [11]. In common, the refractive index can be controlled by manipulating three types of nonlinear effects that occur within the nonlinear resonator cavity which are thermo-optics [12], optical Kerr [13] and carrier induced plasma [14, 15]. The optical Kerr effect is found as the main factor of the optical bistability generation. It enhances by the nonlinear response of the propagated light signal within the optical resonator cavity and with minimum loss of induced light signal [16]. Thus, several experiments and theoretical investigation have been conducted based on the nonlinear Kerr effect for optical switching [17] and optical memory devices [18]. The development of the optical bistability in numerous applications has encourage researchers to explore the nonlinear properties with experimental findings on the various cavities of optical system such as microring waveguide[19], photonics crystal cavities [20, 21], metal gap nanocavities[22], subwavelengths metallic grating [23], and amorphous silicon nanoanntena [24]. The optical resonance effect is found as a key parameter which provided the increase of the optical bistability in which have been investigated in theoretical by using Fabry Perot (FP) configuration in analytical modelling [25]. Besides, the analytical formulation has been developed in optical nanophotonics system for investigating the optical bistability within a nonlinear metal nano-anntena in which able to generate strong field and increase the refractive index changes [25]. The microring resonator (MRR) is one of the promising components in photonics integrated circuit that has potential capability in enhancement of nonlinearity which have been proved in experimental and theoretical investigation that suit with versatile applications including generation of optical bistability [10, 26, 27]. The optical MRR waveguide has been a noteworthy structure that provide nonlinearity in low power consumption due to resonance and confinement of light within the cavity. This allows the MRR to be used for the generation of the optical bistability that can be achieved in low cost and compact size [10, 28]. The design of the MRR configuration is an important factor that can affect the generation and the enhancement of the optical bistability [29]. In year 2008, Yupapin *et al.* has introduced PANDA configuration of MRR system to provide optical switching operation based on the optical bistability effect [30]. The Mobius shape of ring resonator waveguide have been implemented in electrical resonator circuit and optical waveguide resonator [31] for several application such as band-pass filter [32], transmission zero and tunable oscillator [33].

However, in the review of this study, there are still no report on the investigation of the optical bistability based on the optical Mobius ring waveguide whether in theoretical or experimental study. Thus, the theoretical investigation is needed to understand the evolution and enhance the performance of optical bistability in Mobius configuration of MRR system.

1.2 Problem Statement

Optical bistability is an important optical nonlinear property which has many application in all-optical switching devices. The generation of optical bistability behavior is mostly intuitive nonlinearity effect which can be enhanced using the MRR waveguide system. The optical MRR have provided great advancement in the research of the optical science field with numerous application such as the all-optical switching, memory, storage and communication. In recent years, the fabrication of the optical MRR system is focused to demonstrate the fast bistable switching and optical chaotic signal with low input power and the compact size of configurations. Consequently, theoretical and experiment investigations are needed for analyzing the MRR circuits which can contribute to generate and optimize the bistable optical signal. The modelling and simulating of the light propagation within the MRR system are performed with the mathematical derivation of the optical transfer function based on the transfer matrix method and coupled mode theory to study the behavior the optical bistability signal on the proposed configurations. The parameters of the MRR medium such as coupling coefficient, radius of the microring and control power signal are necessary to be investigated for producing a fine nonlinear response to generate an optimized optical bistability hysteresis loop for all-optical switching applications. A clear understanding of fundamental physics optics can be utilized by analyzing the obtained results which governed several subtopic of the photonics fields such as nonlinear effect, optical bistability, scattering matrix, and coupled theory.

1.3 Research Objectives

The general objectives of this research is to study the formation of the optical bistability, using bright soliton pulse within the ring resonator system based on the analytical treatment of the waveguide system.

The specific objectives of this research:

- To design Mobius type of MRR system based on All-pass, Add-drop and PANDA microring resonator configurations.
- To develop the mathematical formulation for deriving the optical transfer function based on conventional and Mobius types MRR configurations.

- To simulate the pulse propagation within MRR systems by using iterative method for modelling the output pulse spectrum and analyzing the output to input power of the MRR configurations.
- To optimize the physical properties of MRR system for enhancing the generation of optical bistability.
- To demonstrate the switching operation based on the spectrum of output signal of MRR configurations.

1.4 Research Scope

This research emphasis on the design of new MRR for generating of optical bistability. The Mobius ring waveguide is implemented into the All-pass, Add-drop and PANDA configuration of MRR. The topological effect of Mobius type configuration is studied in detail in which the ring structure having two different radius per roundtrip. The MRR configuration is simulated based on the physical parameter of Silicon-on-Insulator (SOI) waveguide which consists of the silicon as core and silica as the cladding material. The SOI waveguide fabricated has a linear refractive index of 2.50 [34] and nonlinear refractive index of 4.8×10^{-18} m^2/W [35]. The MRR configurations is simulated by considering the lateral coupling between the main ring and bus waveguide. The derivation of optical transfer function equation is performed based on the coupled mode theory and transfer matrix method. The pulse propagation equations describing the output and circulating electric fields within the MRR systems are obtained by an analytical formulation of the incident optical bright soliton pulses which are fed into the input port of MRR configurations. The simulation of optical electric fields are based on the iterative method of the propagation equation for 200000 roundtrips in order to achieve the optical bistability on the output-to-input power. The parameterization of the waveguide properties is executed by varying the coupling coefficients from 0.4 to 0.9, the ring radius from 1 μm to 6 μm for All-pass and Add-drop types, and 6 to 11 μm PANDA type configuration, and control powers from 50 mW to 100 mW. The input power of the bright soliton is fixed as 50 mW when operating the microring system. The dynamical variation of the optical bistability hysteresis loop is investigated based on the dispersive nonlinear element which relates the change of nonlinear index of the cavity. Several practical parameters such as propagation losses, effective core area, medium index, and attenuation constant are balanced for enhancing the nonlinearity of the waveguide. This will enhances the high performance of optical bistability effect. MATLAB software version 2014a is used to model and simulate the optical spectrum and the hysteresis loop of the optical bistability within MRR configurations.

1.5 Research Significance

The optical bistability is based on the dispersive process. It is found to be important study of nonlinear properties due to its capability of providing the optical switching operation in low power. The contribution of this study is mainly focused on providing the fundamental physics of the optical bistability generation by applying the optical bright soliton pulses that leads to a clear understanding the propagation of the bright soliton pulse within the perspective of nonlinearity theory. There are six configurations of MRRs have been studied to prefigure precisely the performance of optical bistability hysteresis loop for switching operation. The development of theoretical derivation on conventional and proposed Mobius ring waveguide is utilized based on transfer matrix method. These present the basic knowledge on the analytical derivation for optical propagation pulse within a resonator medium. The correlation of the mathematical formulation with nonlinear optics physics have been described based on the modelling of the integrated resonator devices for the enhancement of all-optical switching operation for the information storage, optical transistor and communication applications.

1.6 Thesis Outline

This thesis is divided into six chapters. Chapter 2 will describe the historical and scientific review of optical bistability. In the third chapter, the essential physic concepts nonlinear optics for the formation of temporal optical soliton are discussed.

The waveguide theory has been explained by introducing the optical coupled-mode theory and the transfer matrix analysis for optical field propagation in the medium which correlates MRR, and optical bistability. The mathematical derivation of the optical transmission powers based on propagation equations are examined using transfer matrix analysis and described in detail in Chapter 4. The modelling of the MRR systems are discussed based on the mathematical iterative method which are used for the coding and programming aspect part. There are six configuration of MRR system that are investigated which comprises of three conventional configurations and three Mobius configurations. In Chapter five, the optical pulse propagation within MRR configurations are analyzed and discussed based on numerical modelling using the scattering matrix iterative technique. The linear and nonlinear effects are considered in the numerical models for six configurations of MRR waveguide. The bright soliton pulse with different powers are used for the nonlinear MRR waveguide which provides the chaotics optical signal. The resonance mode of the MRR systems generated the amplified output signal and enhanced the generation of the optical bistability of the system. In Chapter six, concludes the study on optical bistability in Mobius MRR.

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