OPTICAL TWEEZER INDUCED BY MICRORING RESONATOR

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This thesis is dedicated to my parents Abd Aziz Moin and Rosnani Sarmidi,
My beloved family, fiancé and friends,
Thank you for the endless support and encouragement.

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ABSTRACT

Optical tweezer technique for molecular trapping is becoming of increasing importance for numerous biological applications. The main objective of this study was to investigate the dynamical behavior of the optical tweezers signals in microring resonators (MRR). Operating system consists of modified nonlinear add-drop optical filter made of InGaAsP/InP integrated together with a series of nonlinear nanoring resonators. This particular form is known as a PANDA ring resonator. Different models of operating system were designed and optical transfer functions for each model were derived by using Z-transform method. Simulation results were obtained from MATLAB2010a program by using parameters of practical devices. Input signals in the form of dark soliton were generated at center wavelength 1.5 µm with peak intensity 1 W/µm^2 and pulse width 50 ps. Radii of rings were set to be R=34 µm, R_1=60 nm, R_2=60 nm, R_3=50 nm and R_4=50 nm respectively. Coupling coefficients of the system were chosen to be κ_1=0.15, κ_2=0.65, κ_3=0.5, κ_4=0.5, κ_5=0.5 and κ_6=0.50. Intense output signals in the form of potential well are generated at the intensity of 219.14 W/µm^2 and FWHM around 20 nm. Simulated results shows an optical force of 15.83 fN generated from intensity gradient associated with the output signal are calculated for particle of diameter 20 nm. Stiffness at the center of the trap was recorded at 2.23 fN nm^{-1}. This study shows that the model was able to control the dynamical behavior of optical tweezers. Analytical formulation of such system provides the underlying physics of dynamic optical tweezers generation within MRR.

ABSTRAK

Teknik penyepit optik untuk memerangkap molekul menjadi semakin penting bagi pelbagai aplikasi biologi. Objektif utama kajian ini adalah untuk menyelidik sifat dinamik isyarat penyepit optik di dalam pengalun cincin mikro (MRR). Sistem operasi terdiri daripada penapis optik menambah-lepaskan tak linear diubahsuai yang dibuat daripada InGaAsP/InP bersepadu dengan siri pengalun cincin nano yang tidak linear. Sistem ini dikenali sebagai pengalun cincin PANDA. Model sistem operasi yang berlainan telah direka dan fungsi pemindahan optik untuk setiap model diperoleh dengan menggunakan kaedah pemindahan-Z. Hasil simulasi telah diperoleh dengan menggunakan program MATLAB2010a berdasarkan nilai peranti praktikal yang sebenar. Isyarat input dalam bentuk soliton gelap yang dihasilkan pada gelombang yang berpusat pada 1.5 μm dengan keamatan puncak 1 W/μm^2 dan lebar denyut 50 ps. Jejari cincin ditetapkan pada R = 34 μm, R_1 = 60 nm, R_2 = 60 nm, R_3 = 50 nm dan R_4 = 50 nm. Pekali gandingan sistem telah dipilih pada κ_1=0.15, κ_2=0.65, κ_3=0.5, κ_4=0.5, κ_5=0.5 dan κ_6=0.50. Isyarat output dalam bentuk telaga keupayaan dihasilkan pada keamatan 219.14 W/μm^2 dan FWHM sekitar 20 nm. Keputusan simulasi menunjukkan daya optik 15.83 fN telah dijana daripada kecerunan keamatan isyarat output bagi zarah berdiameter 20 nm. Kekukuhan di pusat perangkap dicatatkan pada 2.23 fN nm^{-1}. Kajian ini menunjukkan bahawa model ini mampu untuk mengawal sifat dinamik isyarat penyepit optik. Formulasi analisis sistem tersebut dapat menyediakan pengetahuan asas fizik terhadap penghasilan penyepit optik dinamik di dalam MRR.

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LIST OF SYMBOLS

a - Total loss coefficient of the ring waveguide

α - Attenuation loss

A - Cross sectional area of fiber

Au - Aurum

β - Unperturbed propagation constant

B - Buildup factor

c - Speed of light in vacuum

C - Coupling constant

$\mathrm{C}_{\mathrm{scat}}$ - Scattering cross section parameter

CMT - Coupled mode theory

d - Diameter of the trapped particle

dB - Decibel

D - Group delay dispersion

E - Electric fields

E_{in} - Input signal at input-port

E_{add} - Control signal at add-port

E_t - Output signal at throughput-port

E_d - Output signal at drop-port

ε_{core} - Dielectric constant core fiber

$\varepsilon_{cladding}$ - Dielectric constant cladding fiber

ε_{ij} - Relative permittivity (dielectric constant)

ε_o - Vacuum permittivity

ε_m - Dielectric constant of surrounding medium

ε_n - Dielectric constant of particle

F - Finesse

F_s - Scattering force

F_g - Gradient force

f_o - Incident frequency

FSR - Free spectral range

FWHM - Full width at half maximum

GVD - Group velocity dispersion

h - Planck’s constant

I - Intensity

IDRI - Intensity-dependent refractive index

k - Wavenumber

k_m - Wavenumber of surrounding medium

κ - Coupling coefficient

K - Trap stiffness

L - Circumference length of center ring

L_R - Circumference length of the right ring

L_L - Circumference length of the left ring

m - Integer mode number

m_o - Complex refractive index

n_1 - Real part of refractive index

n_2 - Imaginary part of refractive index

n_{core} - Refractive index of core fiber

$n_{cladding}$ - Refractive index of cladding

p - Linear momentum

ρ - Electric dipole moment

ρ_f - Free charge densities

P - Power/Polarizability

P_L - Linear polarization component

P_{NL} - Nonlinear polarization component

P_{in} - Input power

P_{out} - Output power

Q - Quality factor

$+q$ - Positive charge

$-q$ - Negative charge

r - Radius of particle

R - Radius of center ring

R_R - Radius of right nanoring

R_L - Radius of left nanoring

$<S>$	-	Time average poynting vector
SHG	-	Second harmonic generation
SPM	-	Self-phase modulation
t	-	Time
τ	-	Pulse duration
T	-	Transmission coefficient
μ_o	-	Vacuum permeability
V	-	Volume
W	-	Watt
ω	-	Angular frequency
x	-	Particle’s displacement
χ	-	Electric susceptibility tensor
XPM	-	Cross-phase modulation
γ	-	Intensity insertion loss coefficient
z^{-1}	-	Z-transform parameter
λ	-	Wavelength
λ_o	-	Wavelength in free space
$\Delta\beta_{1/2}$	-	Perturbation of propagation constant
Δn	-	Change in refractive index
θ_1	-	Angles of incidence
θ_2	-	Angles of refraction
ϕ	-	Phase

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Over the past few years, various types of single-molecule force spectroscopy techniques such as optical tweezers, magnetic tweezers and atomic force microscopy (AFM) have been developed to investigate tiny force and motion associated with nano-scaled particle. Among these, optical tweezers are considered as one of the most successful technique for ultrafine positioning, measurement, and confinement of nanoscopic object [1]. Since its interception in early 1970s, the field of optical tweezers has developed rapidly. The capability of this technique to extend the optical trapping down to nanometer-scaled is the main reason why they are frequently used in single-molecular studies [2-5]. Besides, this technique offers a unique property in which it can be used to interact with specific nano-scale object in non-invasive manners. Due to this special ability, conventional optical tweezers techniques have been implemented in various fields of studies ranging from physical chemistry to the medical sciences [6-9]. For instance, biophysics researchers have used optical tweezers to stretch a single strand of DNA in order to observe and study its elasticity and numerous other properties [10, 11]. In other biophysics experiment, this technique has been used to study the motility of human sperm [12]. In chemistry, they used this versatile tool in the process of gold nano-particle trapping. They have successfully demonstrated that metallic materials can be trapped by using this technique [13, 14]. As for atomic physicist, they have also found a use for this technique by trapping individual molecules and atoms for various applications [15-17].

Basically, there are two major types of optical trapping that need to be understood. Both types hold different theory and approximation on explaining how optical tweezers work. Each approximation is used to describe the trapping phenomenon at different scale of particle size relative to the wavelength of the laser beam. The first approximation of trapping is considered when the size of particle is much smaller than the wavelength of laser and this phenomenon is categorized in Rayleigh regime [18]. This approximation can be used to accurately describe the behaviour of the particle in electromagnetic wave under certain condition that requires a small dielectric sphere to be treated as an induced point dipole [19]. Due to the scattering of the electromagnetic waves from the induce dipole, Lorentz force are detected associated with the momentum change of the system. The whole processes give rise to the radiation force on the trapped particle. This force can be separated into two components which are known as gradient and scattering forces [20, 21]. Second type of optical trapping is known as Mie regime. This kind of approximation applied when the wavelength of laser beam much greater than the size of the particle. In this case, ray optic approach is used to evaluate the trapping force on particle. When light is illuminated on the particle, there are photons that being refracted or reflected from the surface. This process shows that there is a momentum being transferred between the incident photons and the particle, thus providing forces to generate the optical trap [22, 23].

Optical tweezers also known as “single-beam gradient force trap” uses a highly focused laser beam to create a large gradient in the intensity of the incident electromagnetic field to trap dielectric objects or biological samples [24]. Technically, this phenomenon occurs by sending the laser beam through an objective lens. Laser beam will be focused to the narrowest point which is known as the beam waist. This is the tiny area that contains a very strong electric field gradient capable of trapping a particle. In conventional optical tweezers set-up, the most essential elements are trapping laser, trapping chamber, beam expander and objective lens with high numerical aperture NA to enhance trapping efficiency. Due to its popularity in increasing number of studies, this technique requires improvements and innovations in all area of instrumentation and technique.

Technical development of such instrument plays a significance role in expanding the use of optical tweezers especially in the fields of nano-biotechnology. Thus, this study focuses on the refinement of the conventional optical tweezers methods and directly provides a novel attempt on constructing optical trapping mechanism/tools by a simpler and smaller practical device which is known as optical microring resonators. An optical microring resonator can be viewed as a set of ordinary waveguide capable of channelling light in a closed loop with specific conditions that allow light to be transmitted inward or outward of the system. This closed geometry formed by the optical waveguide simply forms a resonant cavity that support both transverse and longitudinal mode [25, 26]. Generally, the closed loop waveguide is not necessarily circular shape. It can be designed to have any other closed loop geometry such as eclipse, disk or racetrack [27-30]. Theoretically, the confinement of light and its propagation within the resonant cavity of optical ring resonator can be explained by using total internal reflection (TIR). This unique phenomenon arises due to the different in refractive index of optical fiber.

Microring resonator consists of two main components which are straight and ring waveguides. Those components interact with each other via unidirectional coupler which allow light to be channelled in both direction in the coupling region. Under specific conditions where the optical path length of light roundtrip is a multiple of its effective wavelength, the component of light is said to have resonant with the cavity [31-33]. This spectral component of light is having an intensity “built-up” due to the constructive interference process during propagation inside the ring. This circulating resonant signal can be extracted by using the other straight waveguide that are coupled to the ring [34-36]. Other components of wavelengths that are not in resonance state will bypass it altogether. Thus, by using different coupling configuration on different system, response from the ring resonator can be customly designed. Due to this special characteristic, integrated optical microring resonators have found their way into many interesting applications in various fields of studies.

To date, optical microring resonator has been successfully implemented in optical network as an add-drop filter. Tuneability showed by this filter becoming the main reasons in development and realization of these devices in polymer, semiconductor, active and purely passive material [37-41]. In optical signal processing (OSP) area, microring resonator has been used in the construction of all-optical logic gates system. This device operates based on nonlinear switching mechanism in microring resonator which can be described by changing refractive index of material near critical coupling value [41-44]. This process will induce change in transmission of signals that passing through it. Different transmission properties can be generated by different conditions, thus allowing various logic gates operations [45, 46]. For example, AND and NAND logic gates operations can be performed by using racetrack-shaped resonator [47]. Examples of on-going researches in biological field based on microring resonator are bio-detection and bio-sensing of nanoparticles [48-51]. For instance, semiconductor nanoparticles are usually exploited as fluorescent markers in biomolecule sensing while polymer nanoparticles act as a probe in biological imaging process [52-54].

The primary contribution of this study is on the development of an alternative optical trapping mechanism by introducing the concept of optical microring resonator. This work involves different configurations of optical ring resonator comprises of microring and nanoring resonator integrated together in a single structure. Analytical formulation for each models are derived based on photonics circuit method to produce the signal transfer functions. Such a system can be performed when the input dark soliton and the Gaussian pulse are fed into the specific ports of the microring resonator. Results obtained have shown that output signals generated in the form of dark soliton valley can be configured as molecule/atom trapping potential well. This signal are controlled and tuned to be an optical probe which is known as the optical tweezers. Gradient of intensities from the tweezers signal provides the optical forces to build up the trap. It is shown that field intensity can be altered, in which the desired gradient and scattering forces can be achieved. Analysis shows that change in physical parameters of the system induced the changes in the tweezers characteristics, thus providing a dynamic optical tweezers where the balancing conditions are achieved. Owning to its constitutional small size (micrometer scale) and compact design, this device is very suitable to be built in tiny and complex system especially in nano-bioscience and nano-medicine processes. Directly, this study describes a new concept of developing an optical tweezers source using a dark soliton pulse and leads to expanding of the optical trapping capability into the next level for some practical applications.

1.2 Problem Statement

Optical microring resonator (MRR) studies are becoming important because of the diverse applications ranging from communications to biology. Recently, this device has found its role in development of dynamic optical tweezers by employing the concept of dark soliton pulse controlled by Gaussian pulse within the resonator system. Potential well formed by the gaps of two intensities of the output tweezers signals provides forces to confine atoms. The controlling magnitude of these forces becomes an important task especially when dealing with biological and living cells. During propagation, dark soliton pulse mantains its shape with no observable flunctuation in its power. This indicates that the beam can be used as a transporter without the risk of losing the particles being transported. This technique also has the ability to interact with nano-scaled object in non-invasive manners. Due to these special characteristics offered, development of dynamic optical tweezers by using dark soliton pulse has become typically important with many potential applications. Thus, characterizing and optimizing this system through both modeling and experiment is a crucial step that need to be considered. Relation between keys parameters of the system such as input laser power, coupling coefficients and sizes of the rings with dynamical behaviours of the tweezers signals need to be determined. Development of ring resonator models with its analytical derivations and optimization of the output transmission are formulated. Analyzing and examining the results establish a better understanding on the physics of such system which give a significant contribution to our body of knowledge.

1.3 Objectives of the Study

The main objective of this study is to develop dynamic optical tweezers using a dark soliton pulse controlled by a Gaussian pulse within microring resonator system. The specific objectives of this study are:

1. To design a number of different configurations of the PANDA ring resonator system consisting of micro and nano-size rings.
2. To provide an analytical formulation and derivation of the optical transfer function of the PANDA ring resonator system.
3. To analyze the parametric effects on the dynamical behaviour of the tweezers signals within MRR.
4. To simulate and optimize the model on the desired properties.

1.4 Research Scope

This study focuses on the design and development of optical ring resonator system for generation of optical tweezers pulses. For this purpose, detail examination has been made on several arrangements of integrated ring resonator systems consisting of micro-size ring resonator as the main component and couples of nano-size ring resonators embedded on the structure. The systems consist of a ring resonator, fabricated by using the nonlinear material called InGaAsP/InP with refractive index, n_0=3.34 and the nonlinear refractive index, $n_2 = 2.2 \times 10^{-13}$ m^2/w [55]. The ring and straight waveguide components of the multiple resonators system are laterally coupled together. Optical transfers function for the ring resonator models are obtained by using Z-transform method. Equations governing the dark soliton pulse propagation within optical waveguide and equation of interacting signals within the operating system including output and circulated fields are derived. During processes, coupling coefficients values are set to be in the range of 0 to1 and radius of ring resonator varies from 1 to 100 nm for nanorings and 1 to 50 μm for microrings. Input intensity for the dark soliton signals are varied from 0 to 2 $W/\mu m^2$. Dynamical behaviour of potential well are studied and the corresponding optical forces components acting on the trapped particle are measured by using Rayleigh's dipole approximation theory. Some important aspects including the waveguide losses, effective core areas, refractive index of medium, wavelength, and sizes of trapped particle are tuned to optimize the output tweezers signals. Result are simulated and analyzed by using software MATLAB-2010b.

1.5 Significance of the Research

Dynamic optical tweezers in the form of potential well can been used in frontier research for trapping and transporting dielectric particles, viruses, bacteria, living cells, organelles, small metal particles and even strands of DNA. The significances of this study mainly contribute towards the establishment of the underlying physics of dynamic optical tweezers generation using dark soliton pulses which leads to our understanding on the theory of dark soliton behaviour within ring resonator system. Output signals from different ring resonator models were simulated and parametric influence towards the optical tweezers signals are studied. Thus, these models are able to predict accurately the dynamics behaviour of optical tweezing process for practical operation. Understanding and quantifying the physics of such system gives an insight into the field of microbiology, biological system and drug delivery. This study leaves a direct benefit for scientific awareness of the country, and the whole research activities can be used for future references.

REFERENCES

1. Moffitt JR, C.Y., Izhaky D, Bustamante C, *Differential detection of dual traps improves the spatial resolution of optical tweezers.* Proc. Natl. Acad. Sci USA, 2006. **103**(24): p. 9006-9011.
2. Ai, M., Liu, J. X., Huang, S. S., Wang, G. W., Chen, X. L., Chen, Z. C., and Yao, H. L., *Application and progress of Raman tweezers in single cells.* Fenxi Huaxue/ Chinese Journal of Analytical Chemistry, 2009. **37**(5): p. 758-763.
3. McCauley, M.J. and M.C. Williams, *Optical tweezers experiments resolve distinct modes of DNA-protein binding.* Biopolymers, 2009. **91**(4): p. 265-282.
4. Ichikawa, M., Kubol, K., Murata, S., Yoshikawa, K., and Kimura, Y., *Single cell manipulation by using tilt controlled optical tweezers.* 2007.
5. Neuman, K.C., T. Lionnet, and J.F. Allemand, *Single-molecule micromanipulation techniques.* Annual Review of Materials Research, 2007. **37**: p. 33-67.
6. Li, Y., Wang, G., Yao, H. L., Liu, J. and Li, Y. Q., *Dual-trap Raman tweezers for probing dynamics and heterogeneity of interacting microbial cells.* Journal of Biomedical Optics, 2010. **15**(6).
7. Oehrlein, S.M., Sanchez-Perez, J. R., Jacobson, R. B., Flack, F. S., Kershner, R. J. and Lagally, M. G., *Translation and manipulation of silicon nanomembranes using holographic optical tweezers.* Nanoscale Research Letters, 2011. **6**: p. 1-7.
8. Raghunathan, K., J.N. Milstein, and J.C. Meiners, *Stretching short sequences of DNA with constant force axial optical tweezers.* Journal of visualized experiments : JoVE, 2011(56).

9. Winther, T. and L.B. Oddershede, *Effect of antibiotics and antimicrobial peptides on single protein motility*. Current Pharmaceutical Biotechnology, 2009. **10**(5): p. 486-493.
10. Yan, J., D. Skoko, and J.F. Marko, *Near-field-magnetic-tweezer manipulation of single DNA molecules.* Physical Review E - Statistical, Nonlinear, and Soft Matter Physics, 2004. **70**(1 1): p. 011905-1-011905-5.
11. Crisafuli, F.A.P., Cesconetto, E. C., Ramos, E. B. and Rocha, M. S., *DNA-cisplatin interaction studied with single molecule stretching experiments.* Integrative Biology, 2012. **4**(5): p. 568-574.
12. Ohta, A.T., Garcia, M., Valley, J. K., Jamshidi, A., Lue, T. and Wu, M. C., *Motile and non-motile sperm diagnostic manipulation using optoelectronic tweezers.* Lab on a Chip - Miniaturisation for Chemistry and Biology, 2010. **10**(23): p. 3213-3217.
13. Hajizadeh, F. and S.N.S. Reihani, *Optimized optical trapping of gold nanoparticles.* Optics Express, 2010. **18**(2): p. 551-559.
14. Albaladejo, S., Marqués, M. I., Scheffold, F. and Sáenz, J. J., *Giant enhanced diffusion of gold nanoparticles in optical vortex fields.* Nano Letters, 2009. **9**(10): p. 3527-3531.
15. Chen, W.H., Wilson, J. D., Wijeratne, S. S., Southmayd, S. A., Lin, K. J. and Kiang, C. H., *Principles of single-molecule manipulation and its application in biological physics.* International Journal of Modern Physics B, 2012. **26**(13).
16. Ashkin, A., *History of optical trapping and manipulation of small-neutral particle, atoms, and molecules.* IEEE Journal on Selected Topics in Quantum Electronics, 2000. **6**(6): p. 841-856.
17. Calander, N. and M. Willander, *Optical trapping of single fluorescent molecules at the detection spots of nanoprobes.* Physical Review Letters, 2002. **89**(14): p. 143603/1-143603/4.
18. Bonessi, D., K. Bonin, and T. Walker, *Optical forces on particles of arbitrary shape and size.* Journal of Optics A: Pure and Applied Optics, 2007. **9**(8): p. S228-S234.
19. M. Dienerowitz, M. Mazilu, and K. Dholakia, *Optical manipulation of nanoparticles:a review.* Journal of Nanophotonics, 2008. **2**(1): p. 021857.

20. Liu, Z. and D. Zhao, *Radiation forces acting on a Rayleigh dielectric sphere produced by highly focused elegant Hermite-cosine-Gaussian beams.* Optics Express, 2012. **20**(3): p. 2895-2904.
21. Harada, Y. and T. Asakura, *Radiation forces on a dielectric sphere in the Rayleigh scattering regime.* Optics Communications, 1996. **124**(5-6): p. 529-541.
22. Stilgoe, A.B., Nieminen, T. A., Knöener, G., Heckenberg, N. R. and Rubinsztein-Dunlop, H., *The effect of Mie resonances on trappingin optical tweezers.* Opt. Express, 2008. **16**(19): p. 15039-15051.
23. Ke, P.C. and M. Gu, *Characterization of trapping force on metallic Mie particles.* Applied Optics, 1999. **38**(1): p. 160-167.
24. Fazal, F.M. and S.M. Block, *Optical tweezers study life under tension.* Nature Photonics, 2011. **5**(6): p. 318-321.
25. Qiu, C. and Q. Xu, *Controlling normal incident optical waves with an integrated resonator.* Optics Express, 2011. **19**(27): p. 26905-26910.
26. Turner, A.C., Foster, M. A., Gaeta, A. L. and Lipson, M., *Ultra-low power parametric frequency conversion in a silicon microring resonator.* Optics Express, 2008. **16**(7): p. 4881-4887.
27. Bergeron, S., F. Vanier, and Y.A. Peter. *Silica microdisk coupled resonator optical waveguide*. 2009.
28. Alipour, P., Hosseini, E. S., Eftekhar, A. A., Momeni, B. and Adibi, A., *Athermal operation in polymer-clad silicon microdisk resonators*. 2009.
29. Masi, M., Orobtchouk, R., Fan, G., Fedeli, J. M. and Pavesi, L., *Towards a realistic modelling of ultra-compact racetrack resonators.* Journal of Lightwave Technology, 2010. **28**(22): p. 3233-3242.
30. Timotijevic, B.D., Gardes, F. Y., Headley, W. R. and Masanovic, G. Z., *Multi-stage racetrack resonator filters in silicon-on-insulator.* Journal of Optics A: Pure and Applied Optics, 2006. **8**(7): p. S473-S476.
31. Zhang, L., Li, Y., Yang, J. Y., Song, M., Beausoleil, R. G. and Willner, A. E., *Silicon-based microring resonator modulators for intensity modulation.* IEEE Journal on Selected Topics in Quantum Electronics, 2010. **16**(1): p. 149-158.
32. Heebner, J., R. Grover, and T. Ibrahim, *Introduction to Optical Microresonators*. 2008, Springer Berlin / Heidelberg. p. 1-7.

33. Mookherjea, S. and A. Yariv. *Pulse propagation in coupled resonator optical waveguides*. 2002.

34. Manolatou, C., Khan, M. J., Fan, S., Haus, H. A. and Joannopoulos, J. D., *Coupling of modes analysis of resonant channel add-drop filters.* Quantum Electronics, IEEE Journal of, 1999. **35**(9): p. 1322-1331.

35. Islam, M.M., *Analysis of add/drop optical waveguide filters with embedded resonant cavities using the method of lines,* in *Electrical Engineering*. 2005, King Fahd University of Petroleum & Minerals Dhahran.

36. Little, B.E., Chu, S. T., Haus, H. A., Foresi, J. and Laine, J. P., *Microring resonator channel dropping filters.* Journal of Lightwave Technology, 1997. **15**(6): p. 998-1005.

37. Scheuer, J., G.T. Paloczi, and A. Yariv, *All optically tunable wavelength-selective reflector consisting of coupled polymeric microring resonators.* Applied Physics Letters, 2005. **87**(25): p. 1-3.

38. Poon, J.K.S., Zhu, L., DeRose, G. A. and Yariv, A., *Polymer microring coupled-resonator optical waveguides.* Journal of Lightwave Technology, 2006. **24**(4): p. 1843-1849.

39. Heebner, J.E., Lepeshkin, N. N., Wicks, G. W., Boyd, R. W., Grover, R. and Ho, P. T., *Enhanced linear and nonlinear optical phase response of AlGaAs microring resonators.* Optics Letters, 2004. **29**(7): p. 769-771.

40. Niehusmann, J., Vörckel, A., Bolivar, P. H., Wahlbrink, T., Henschel, W. and Kurz, H., *Ultrahigh-quality-factor silicon-on-insulator microring resonator.* Optics Letters, 2004. **29**(24): p. 2861-2863.

41. Xu, Q., D. Fattal, and R.G. Beausoleil, *Silicon microring resonators with 1.5-μm radius.* Optics Express, 2008. **16**(6): p. 4309-4315.

42. Yariv, A., *Critical coupling and its control in optical waveguide-ring resonator systems.* IEEE Photonics Technology Letters, 2002. **14**(4): p. 483-485.

43. Green, W.M.J., Lee, R. K., Yariv, A. and Scherer, A., *Control of optical waveguide-resonator coupling: Applications to low-power optical modulation and switching*. 2003.

44. McAulay, A., *Nonlinear microring resonators forge all-optical switch.* Laser Focus World, 2005. **41**(11): p. 127-130.

45. Ibrahim, T.A., Amarnath, K., Kuo, L. C., Van, V. and Ho, P. T., *Photonic logic NOR gate based on two symmetric microring resonators.* Optics Letters, 2004. **29**(23): p. 2779-2781.
46. Isfahani, B.M., Tameh, T. A., Granpayeh, N. and Javan, A. R. M., *All-optical NOR gate based on nonlinear photonic crystal microring resonators.* Journal of the Optical Society of America B: Optical Physics, 2009. **26**(5): p. 1097-1102.
47. Ibrahim, T.A., Grover, R., Kuo, L. C., Kanakaraju, S and Ho, P. T., *All-optical AND/NAND logic gates using semiconductor microresonators.* Photonics Technology Letters, IEEE, 2003. **15**(10): p. 1422-1424.
48. Haddadpour, A. and Y. Yi, *Metallic nanoparticle on micro ring resonator for bio optical detection and sensing.* Biomed. Opt. Express, 2010. **1**(2): p. 378-384.
49. Li, X., Zhang, Z., Qin, S., Qiu, M. and Su, Y., *Ultra-compact parallel label-free biosensors based on concentric micro-ring resonators in silicon-on-insulator*. 2008.
50. Li, X., Zhang, Z., Qin, S., Qiu, M. and Su, Y., *Label-free biosensor based on silicon-on-insulator micro-ring resonators*. 2008.
51. Luchansky, M.S. and R.C. Bailey, *Silicon photonic microring resonators for quantitative cytokine detection and T-cell secretion analysis.* Analytical Chemistry, 2010. **82**(5): p. 1975-1981.
52. Wiese, R., *Analysis of several fluorescent detector molecules for protein microarray use.* Luminescence, 2003. **18**(1): p. 25-30.
53. Yuan, Z., Kardynal, B. E., Stevenson, R. M., Shields, A. J., Lobo, C. J., Beattie, N. S., Ritchie, D. A. and Pepper, M., *Electrically driven single-photon source.* Science, 2002. **295**(5552): p. 102-105.
54. Chen, S.L., Huang, S. W., Ling, T., Ashkenazi, S. and Guo, L. J., *Polymer microring resonators for high-sensitivity and wideband photoacoustic imaging.* IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2009. **56**(11): p. 2482-2491.
55. Thongmee, S. and P.P. Yupapin, *Chaotic soliton switching generation using a nonlinear micro ring resonator for secure packet switching use.* Optik (Stuttg), 2010. **121**(3): p. 5-5.

56. Svoboda, K. and S. Block, *Biological applications of optical forces.* Annual review of biophysics and biomolecular structure, 1994. **23**(1): p. 247-285.

57. Ashkin, A., *History of optical trapping and manipulation of small-neutral particle, atoms, and molecules.* IEEE Journal on Selected Topics in Quantum Electronics, 2000. **6**(4): p. 841-856.

58. Ashkin, A., *Acceleration and Trapping of Particles by Radiation Pressure.* Physical Review Letters, 1970. **24**(4): p. 156-159.

59. Ashkin, A. and J.M. Dziedzic, *Optical Levitation by Radiation Pressure.* Applied Physics Letters, 1971. **19**(8): p. 283-285.

60. Ashkin, A. and J.M. Dziedzic, *Optical Levitation of Liquid Drops by Radiation Pressure.* Science, 1975. **187**(4181): p. 1073-1075.

61. Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E. and Chu, Steven, *Observation of a single-beam gradient force optical trap for dielectric particles.* Opt. Lett., 1986. **11**(5): p. 288-290.

62. Ashkin, A. and J.M. Dziedzic, *Optical trapping and manipulation of virusses and bacteria.* Science, 1987. **235**(4795): p. 1517-1520.

63. Svoboda, K. and S.M. Block, *Optical trapping of metallic Rayleigh particles.* Opt. Lett., 1994. **19**(13): p. 930-932.

64. Ashkin, A., *Optical trapping and manipulation of neutral particles using lasers.* Proceedings of the National Academy of Sciences, 1997. **94**(10): p. 4853-4860.

65. Pralle, A., M. Prummer, E. L. Florin, E. H. Stelzer and J. K. Horber, *Three-Dimensional High-Resolution Particle Tracking for Optical Tweezers by Forward Scattered Light.* Microscopy Research and Technique, 2000. **44**(5): p. 378-386.

66. Ishii, Y., A. Ishijima, and T. Yanagida, *Single molecule nanomanipulation of biomolecules.* Trends in Biotechnology, 2001. **19**(6): p. 211-216.

67. MacDonald, M.P., G.C. Spalding, and K. Dholakia, *Microfluidic sorting in an optical lattice.* Nature, 2003. **426**(6965): p. 421-424.

68. Applegate, J.R., Squier, Jeff, Vestad, Tor, Oakey, John and Marr, David, *Optical trapping, manipulation, and sorting of cells and colloids in microfluidic systems with diode laser bars.* Opt. Express, 2004. **12**(19): p. 4390-4398.

69. Moffitt, J.R., Chemla, Yann R., Izhaky, David and Bustamante, Carlos, *Differential detection of dual traps improves the spatial resolution of optical tweezers.* Proceedings of the National Academy of Sciences, 2006. **103**(24): p. 9006-9011.

70. Zakharian, A.R., Polynkin, P., Mansuripur, M. and Moloney, J. V., *Single-beam trapping of micro-beads in polarized light: Numerical simulations.* Optics Express, 2006. **14**(8): p. 3660-3676.

71. Nieminen, T.A., Loke, V. L. Y., Stilgoe, A. B., Knöner, G., Brańczyk, A. M. and Rubinsztein-Dunlop, H., *Optical tweezers computational toolbox.* Journal of Optics A: Pure and Applied Optics, 2007. **9**(8): p. S196-S203.

72. Taylor, R. and C. Hnatovsky, *Particle trapping in 3-D using a single fiber probe with an annular light distribution.* Opt. Express, 2003. **11**(21): p. 2775-2782.

73. Ikeda, M., Tanaka, K., Kittaka, M., Tanaka, M. and Shohata, T., *Rotational manipulation of a symmetrical plastic micro-object using fiber optic trapping.* Optics Communications, 2004. **239**(1–3): p. 103-108.

74. Liu, Z., Guo, C., Yang, J. Y. and Yuan, Libo, *Tapered fiber optical tweezers for microscopic particle trapping: fabrication and application.* Opt. Express, 2006. **14**(25): p. 12510-12516.

75. Minzioni, P., Bragheri, F., Liberale, C., Di Fabrizio, E. and Cristiani, I., *A Novel Approach to Fiber-Optic Tweezers: Numerical Analysis of the Trapping Efficiency.* Selected Topics in Quantum Electronics, IEEE Journal of, 2008. **14**(1): p. 151-157.

76. O'Dwyer, D.P., Phelan, C. F. and Donegan, J. F., *An optical trap based on conical refraction of light.* Optical Trapping and Optical Micromanipulation VIII, 2011. **8097:** p. 6.

77. Brzobohaty, O., Karásek, V., Čižmár, T. and Zemánek, P., *Demonstration of multi-dimensional optical binding in counter-propagating laser beams with variable beam properties.* Optical Trapping and Optical Micromanipulation VIII, 2011. **8097:** p. 8.

78. Mas, J., Farré, A., López-Quesada, C., Fernández, X., Martín-Badosa, E. and Montes-Usategui, M., *Measuring stall forces in vivo with optical tweezers through light momentum changes.* Optical Trapping and Optical Micromanipulation VIII, 2011. **8097:** p. 10.

79. Huss, A., Chizhik, A. M., Jäger, R., Chizhik, A. I. and Meixner, A. J., *Optical trapping of gold nanoparticles using a radially polarized laser beam.* Optical Trapping and Optical Micromanipulation VIII, 2011. **8097:** p. 20.

80. Mitatha, S., Moongfangklang, N., Jalil, M. A., Suwanpayak, N., Ali, J. and Yupapin, P. P., *Multi-access drug delivery network and stability.* International journal of nanomedicine, 2011. **6**: p. 1757-1764.

81. Mitatha, S., Moongfangklang, N., Jalil, M. A., Suwanpayak, N., Saktioto, T., Ali, J. and Yupapin, P. P., *Proposal for Alzheimer's diagnosis using molecular buffer and bus network.* International journal of nanomedicine, 2011. **6**: p. 1209-1216.

82. Suwanpayak, N., Jalil, M. A., Aziz, M. S., Ismail, F. D., Ali, J. and Yupapin, P. P., *Blood cleaner on-chip design for artificial human kidney manipulation.* International journal of nanomedicine, 2011. **6**: p. 957-964.

83. Marcatili, E.A.J., *Bends in optical dielectric guides.* Bell System Tech J, 1969. **48**(7): p. 2103-2132.

84. Weber, H.P. and R. Ulrich, *A thin-film ring laser.* Applied Physics Letters, 1971. **19**(2): p. 38-40.

85. Ulrich, R. and H.P. Weber, *Unidirectional thin-film ring laser.* Applied Physics Letters, 1972. **20**(1): p. 38-40.

86. Haavisto, J. and G.A. Pajer, *Resonance effects in low-loss ring waveguides.* Opt. Lett., 1980. **5**(12): p. 510-512.

87. Stokes, L.F., M. Chodorow, and H.J. Shaw, *All-single-mode fiber resonator.* Opt. Lett., 1982. **7**(6): p. 288-290.

88. Walker, R.G. and C.D. Wilkinson, *Integrated optical ring resonators made by silver ion-exchange in glass.* Applied Optics, 1983. **22**: p. 1029-1035.

89. Mahapatra, A. and J.M. Connors, *High finesse ring resonators made by silver ion exchange in glass.* journal of Lightwave Technology, 1987. **5**: p. 1686-1689.

90. Honda, K., Garmire, and K.E. Wilson, *Characteristics of an integrated optics ring resonator fabricated in glass.* Journal of Lightwave Technology, 1984. **2**: p. 714-719.

91. Chu, D.Y., M. K. Chin, N. J. Sauer and Z. Xu., *InGaAs/InAlGa As quantum-well microdisk lasers.* IEEE Photonics Technology Letters, 1993. **5**: p. 1353-1355.

92. Mair, R.A., *Optical modes within III–nitride multiple quantum well microdisk cavities.* Applied Physics Letters, 1998. **72**(1530-1532).

93. Dai, L., B. Zhang, R. A. Mair, K. Zeng, J. Lin, H. Jigang, A. Botchkarev and M. A. Khan, *Optical properties and resonant modes in GaN/AlGaNandInGaN/GaN multiple quantum well microdisk cavities.* Semiconductor Lasers III, Beijing, China, 1998.

94. Baba, T., P. Fujita, A. Sakai, M. Kihara and R. Watanabe, *Lasing characteristics of GaInAsP-InP strained quantum-well microdisk injection lasers with diameter of* $2-10\ \mu m$*.* IEEE Photonics Technology Letters, 1997. **9**: p. 878-880.

95. Rafizadeh, D., *Experimental realization of nanofabricated semiconductor waveguide-coupled microcavity ring and disk optical resources.* 1997, Northwestern University.

96. Absil, P.P., Hryniewicz, J. V., Little, B. E., Wilson, R. A., Joneckis, L. G. and Ho, P. T., *Compact microring notch filters.* IEEE Photonics Technology Letters, 2000. **12**(4): p. 398-400.

97. Absil, P.P., Hryniewicz, J. V., Little, B. E., Cho, P. S., Wilson, R. A., Joneckis, L. G. and Ho, P. T., *Wavelength conversion in GaAs micro-ring resonators.* Optics Letters, 2000. **25**(8): p. 554-556.

98. Absil, P.P., *Microring resonators for wavelength division multiplexing and integrated photonics applications.* 2000, University of Maryland: College Park.

99. Rabus, D.G., M. Hamacher, and H. Heidrich, *Resonance frequency tuning of a double ring resonator in GaInAsP/InP: Experiment and simulation.* Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers, 2002. **41**(2 B): p. 1186-1189.

100. Rabus, D.G., Hamacher, M., Heidrich, H. and Troppenz, U., *Box-like filter response of triple ring resonators with integrated SOA sections based on GaInAsP/InP*. 2002.

101. Rabus, D.G. and M. Hamacher, *MMI-coupled ring resonators in GaInAsP-InP.* IEEE Photonics Technology Letters, 2001. **13**(8): p. 812-814.

102. Rabus, D.G., Hamacher, M., Heidrich, H. and Troppenz, U., *High-Q channel-dropping filters using ring resonators with integrated SOAs.* IEEE Photonics Technology Letters, 2002. **14**(10): p. 1442-1444.

103. Rabus, D.G., Hamacher, M., Heidrich, H. and Troppenz, U., *Optical filters based on ring resonators with integrated semiconductor optical amplifiers in GaInAsP-InP*. IEEE Journal on Selected Topics in Quantum Electronics, 2002. **8**(6): p. 1405-1411.

104. Rabus, D.G., *Realization of Optical Filters using Ring Resonators with integrated Semiconductor Optical Amplifiers in GaInAsP/Inp,* in *Elektrotechnik und Informatik.* 2002, Heinrich-Hertz Institut fur Nachrichtentechnik: Berlin.

105. Djordjev, K., S.J. Choi, and P.D. Dapkus, *Vertically coupled InP microdisk switching devices with electroabsorptive active regions.* IEEE Photonics Technology Letters, 2002. **14**(8): p. 1115-1117.

106. Djordjev, K., *Active microdisk resonant devices and semiconductor optical equalizers as building blocks for future photonic circuitry*. 2002, University of Southern California: California.

107. Djordjev, K., S.J. Choi, and P.D. Dapkus, *Active semiconductor microdisk devices.* Journal of Lightwave Technology, 2002. **20**(1): p. 105-113.

108. Rabiei, P. and W.H. Steier, *Tunable polymer double micro-ring filters.* IEEE Photonics Technology Letters, 2003. **15**(9): p. 1255-1257.

109. Tan, F., *Integrated optical filters based on microring resonators*. 2004, University of Twente.

110. Geuzebroek, D., *Flexible optical network components based on densely integrated microring resonators*. 2005, University of Twente.

111. Poon, J., Scheuer, J., Mookherjea, S., Paloczi, G. T., Huang, Y. and Yariv, A., *Matrix analysis of microring coupled-resonator optical waveguides.* Opt. Express, 2004. **12**(1): p. 90-103.

112. Rabiei, P., *Calculation of losses in micro-ring resonators with arbitrary refractive index or shape profile and its applications.* Lightwave Technology, Journal of, 2005. **23**(3): p. 1295-1301.

113. Yupapin, P.P., N. Pornsuwancharoen, and S. Chaiyasoonthorn, *Attosecond pulse generation using the multistage nonlinear microring resonators.* Microwave and Optical Technology Letters, 2008. **50**(12): p. 3108-3111.

114. Polar, A., Threepak, T., Mitatha, S., Bunyatnoparat, P. and Yupapin, P. P., *New wavelength division multiplexing bands generated by using a Gaussian pulse in a microring resonator system*. 2009.

115. Mitatha, S., R. Putthacharoen, and P.P. Yupapin, *THz frequency bands generation for Radio-over-Fiber systems.* Optik - International Journal for Light and Electron Optics, 2012. **123**(11): p. 974-977.

116. Tasakorn, M., N. Suwanpayak, and P. Yupapin, *Blood circulation network incorporation an artificial bone for real time operation.* 2012. p. 102-105.

117. Aziz, M.S., Suwanpayak, N., Jalil, M. A., Jomtarak, R., Saktioto, T., Ali, J. and Yupapin, P. P., *Gold nanoparticle trapping and delivery for therapeutic applications.* International journal of nanomedicine, 2012. **7**: p. 11-17.

118. Jalil, M.A., Innate, K., Suwanpayak, N., Yupapin, P. P. and Ali, J., *Molecular diagnosis using multi drug delivery network and stability.* Artificial Cells, Blood Substitutes, and Biotechnology, 2011. **39**(6): p. 357-365.

119. Neuman, K.C. and S.M. Block, *Optical trapping.* Review of Scientific Instruments, 2004. **75**(9): p. 2787-2809.

120. Guck, J., Ananthakrishnan, R., Mahmood, H., Moon, T. J., Cunningham, C. C. and Käs, J., *The Optical Stretcher: A Novel Laser Tool to Micromanipulate Cells.* Biophysical journal, 2001. **81**(2): p. 767-784.

121. L. Wilson, R. Besseling, J.Arlt, W.C.K.Poon, K. Dholakia and G.C. Spalding, *Optical Trapping and Optical Micromanipulation II.* SPIE, 2005. **5930**: p. 71.

122. M.D.Summers, *Optical Manipulation of Aerosols*, in *School of Physics and Astronomy*. 2009, Universitu of St. Andrews.

123. Barton, J.P., *Internal and near-surface electromagnetic fields for a spheroidal particle with arbitrary illumination.* Appl. Opt., 1995. **34**(24): p. 5542-5551.

124. Rodrigo, P., V. Daria, and J. Glückstad, *Real-time interactive optical micromanipulation of a mixture of high-and low-index particles.* Opt. Express, 2004. **12**(7): p. 1417-1425.

125. Grier, D.G., *A revolution in optical manipulation.* Nat Photon, 2003. **424**(6950): p. 810-816.

126. Parkin, S., Knöner, G., Nieminen, T. A., Heckenberg, N. R. Rubinsztein-Dunlop, H., *Measurement of the total optical angular momentum transfer in optical tweezers.* Opt. Express, 2006. **14**(15): p. 6963-6970.

127. Grange, W., Husale, S., Guntherodt, Hans-Joachim and Hegner, M., *Optical tweezers system measuring the change in light momentum flux.* Review of Scientific Instruments, 2002. **73**(6): p. 2308-2316.

128. Dholakia, K. and W.M. Lee, *Optical Trapping Takes Shape: The Use of Structured Light Fields,* in *Advances In Atomic, Molecular, and Optical Physics,* Arimondo and *et al.*, Editors. 2008, Academic Press. p. 261-337.

129. Nieminen, T.A., Knöner, G. and Heckenberg, N. R., *Physics of Optical Tweezers,* in *Methods in Cell Biology,* W.B. Michael and G. Karl Otto, Editors. 2007, Academic Press. p. 207-236.

130. Smith, S.B., Y. Cui, and C. Bustamante, *[7] Optical-trap force transducer that operates by direct measurement of light momentum,* in *Methods in Enzymology,* M. Gerard and P. Ian, Editors. 2003, Academic Press. p. 134-162.

131. Douglas, B., B. Keith, and W. Thad, *Optical forces on particles of arbitrary shape and size.* Journal of Optics A: Pure and Applied Optics, 2007. **9**(8): p. S228.

132. Gu, M. and D. Morrish, *Three-dimensional trapping of Mie metallic particles by the use of obstructed laser beams.* Journal of Applied Physics, 2002. **91**(3): p. 1606-1612.

133. Ashkin, A., *Forces of a single-beam gradient laser trap on a dielectric sphere in the ray optics regime.* Methods in Cell Biology, 1998. **55**: p. 1-27.

134. Zemánek, P., A. Joná, and M. Li?ka, *Simplified description of optical forces acting on a nanoparticle in the Gaussian standing wave.* J. Opt. Soc. Am. A, 2002. **19**(5): p. 1025-1034.

135. Jonás, A., P. Zemánek, and E.-L. Florin, *Single-beam trapping in front of reflective surfaces.* Opt. Lett., 2001. **26**(19): p. 1466-1468.

136. Barton, J.P., *Expansion of an arbitrarily oriented, located, and shaped beam in spheroidal coordinates.* journal of Appl. Phys., 1988. **64**: p. 1632-1640.

137. Han, Y., G. Gréhan, and G. Gouesbet, *Generalized Lorenz-Mie Theory for a Spheroidal Particle with Off-Axis Gaussian-Beam Illumination.* Appl. Opt., 2003. **42**(33): p. 6621-6629.

138. Gouesbet, G., *Generalized Lorenz–Mie theories, the third decade: A perspective.* Journal of Quantitative Spectroscopy and Radiative Transfer, 2009. **110**(14–16): p. 1223-1238.

139. Rohrbach, A. and E.H.K. Stelzer, *Trapping forces, force constants, and potential depths for dielectric spheres in the presence of spherical aberrations.* Applied Optics, 2002. **41**(13): p. 2494-2507.

140. Rohrbach, A. and E.H.K. Stelzer, *Optical trapping of dielectric particles in arbitrary fields.* Journal of the Optical Society of America A: Optics and Image Science, and Vision, 2001. **18**(4): p. 839-853.

141. Lock, J.A. and G. Gouesbet, *Generalized Lorenz–Mie theory and applications.* Journal of Quantitative Spectroscopy and Radiative Transfer, 2009. **110**(11): p. 800-807.

142. Rohrbach, A. and E.H.K. Stelzer, *Optical trapping of dielectric particles in arbitrary fields.* J. Opt. Soc. Am. A, 2001. **18**(4): p. 839-853.

143. Zhan, Q., *Trapping metallic Rayleigh particles with radial polarization.* Opt. Express, 2004. **12**(15): p. 3377-3382.

144. Hopkins, R.J., Mitchem, L., Ward, A. D. and Reid, J. P., *Control and characterisation of a single aerosol droplet in a single-beam gradient-force optical trap.* Physical Chemistry Chemical Physics, 2004. **6**(21): p. 4924-4927.

145. Garbin, V., Cojoc, D., Kulkarni, R., Malureanu, R., Ferrari, E., Nadasan, M. and Di Fabrizio, E., *Numerical analysis of forces in optical tweezers in the Rayleigh regime.* 2005: p. 597205-597205.

146. Lin, Q., Z. Wang, and Z. Liu, *Radiation forces produced by standing wave trapping of non-paraxial Gaussian beams.* Optics Communications, 2001. **198**(1–3): p. 95-100.

147. Harada, Y. and T. Asakura, *Radiation forces on a dielectric sphere in the Rayleigh scattering regime.* Optics Communications, 1996. **124**(5–6): p. 529-541.

148. Zemánek, P., Jonáš, A., Šrámek, L. and Liška, M., *Optical trapping of Rayleigh particles using a Gaussian standing wave.* Optics Communications, 1998. **151**(4–6): p. 273-285.

149. Hahn, D.W., *Light scattering theory.* Department of Mechanical and Aeorospace Engineering, University of Florida, 2006.

150. Hahn, D., *Light Scattering theory. Department of Mechanical and Aerospace Engineering, University of Florida.* 2004.

151. Agrawal, G.P., *Nonlinear Fiber Optics.* third ed. 2001, New York: Academic Press.

152. L.F.Mollenauer and J.P.Gordon, *Solitons in Optical Fibers.* Fundamentals and Applications. 2006, San Diego, CA: Academic Press.

153. Butcher, P.N. and D. Cotter, *The Elements of Nonlinear Optics*. 1990: Cambridge University Press.

154. Bloembergen, N., *Nonlinear Optics (4th Edition)*. 1996: World Scientific Publ.

155. Weinberger, P., *John Kerr and his effects found in 1877 and 1878.* Philosophical Magazine Letters, 2008. **88**(12): p. 897-907.

156. Boyd, R.W., *Nonlinear Optics*. 2008: Elsevier Science.

157. S.P.Singh and N.Singh, *Nonlinear effects in optical fibers: origin, management and applications.* Progress In Electromagnetics Research, 2007. **73**: p. 249-275.

158. Melnichuk, M. and L.T. Wood, *Direct Kerr electro-optic effect in noncentrosymmetric materials.* Physical Review A, 2010. **82**(1): p. 013821.

159. Yang, Y., Lou, Caiyun, Zhou, Hongbo, Wang, Jiajun and Gao, Yizhi, *Simple pulse compression scheme based on filtering self-phase modulation-broadened spectrum and its application in an optical time-division multiplexing system.* Appl. Opt., 2006. **45**(28): p. 7524-7528.

160. Saleh, B.E.A. and M.C. Teich, *Fundamentals of Photonics*. 2007: John Wiley & Sons.

161. Chen, C.L., *Foundations for Guided-Wave Optics*. 2006: Wiley.

162. Pornsuwancharoen, N., J. Ali, and P.P. Yupapin, *Optical Solitons in Nonlinear Micro Ring Resonators: Unexpected Results and Applications.* 2009: Nova Science Pub.

163. Raji, A.W.M., Rahmat H., Kamis I., Mohamad M. N. and Tiong O. C., *Intermediate mathematics for science and engineering students*. 2004, Johor Bahru: Comtech Marketing Sdn. Bhd.

164. Rabus, D.G., *Integrated Ring Resonators: The Compendium*. 2010: Springer.

165. Attaway, S., *Matlab, Second Edition: A Practical Introduction to Programming and Problem Solving*. Vol. 2. 2011.

166. Fangohr, H., *A comparison of C, Matlab and Python as teaching languages in engineering.* Computational Science-ICCS, 4th International Conference, Kraków, Poland, 2004. **3039**.

167. Liu, X. and F. Wang. *Influence of the laser parameters on trapping gold nanoparticles*. in *Laser Physics and Laser Technologies (RCSLPLT) and*

2010 Academic Symposium on Optoelectronics Technology (ASOT), 2010 10th Russian-Chinese Symposium on. 2010.