Nonlinear Optics and Applications

Edited by
Hossin A. Abdeldayem, Ph.D.
NASA-Goddard Space Flight Center
Greenbelt, Maryland, USA

And
Donald O. Frazier, Ph.D.
NASA-Marshall Space Flight Center
Huntsville, Alabama, USA
Nonlinear optics is the result of laser beam interaction with materials and started with the advent of lasers in the early 60’s. It has already reached the level of maturity and has been proven to be an exciting field, that is growing dramatically every day and is playing a major role in the emerging photonic technology. Nonlinear optics led to countless optical devices that have become indispensable in our daily lives. Nonlinear optics played a major role in many of the optical applications such as optical signal processing, optical computers, ultrafast switches, ultra-short pulsed lasers, sensors, laser amplifiers, and many others. This special review volume on Nonlinear Optics and Applications is intended for those who want to be aware of the most recent developments in photonics and the role of nonlinear optics in photonic technology. It is also important to note that the research work in nonlinear optics, optical materials, and nonlinear optics devices in the last five years is enormous and is beyond comprehending it all in one book, which made our job extremely difficult to give a complete fair coverage of all the great published ideas. Consequently, we apologize in advance to those whose significant work was accidentally left out.

In this book, we give a survey on the recent advances of nonlinear optical applications. Emphasis will be on novel devices and materials, switching technology, optical computing, and important experimental results. We also include the recent developments in topics which are of historical interest to many researchers, and in the same time of potential to be used in the fields of all-optical communication and computing technologies. In addition, we enclosed a few new and unconventional related topics which might provoke new thinking and discussions. This review volume will be of interest for a broad range of research scientists, engineers, and graduate students in multidiscipline research areas such as optics, material science, chemistry, physics, lasers, fibers, semiconductors, computer and electrical engineering.

The book is organized as follows: Chapter 1 provides an introduction to nonlinear optics and applications particularly as related to organic \( \pi \)-electron materials and devices fabricated from such materials. It provides insight into the fundamental concepts and guiding principles leading to improved materials and devices. Chapter 2 provides a brief review of the nonlinear Schrodinger and associated equations that model spatio-temporal propagation in one and higher dimensions in nonlinear dispersive media. Fast adaptive numerical techniques were used to solve these equations. A unique variational approach is also outlined that helps in determining the ranges of nonlinearity and dispersion parameters. Chapter 3 is an update of the supercontinuum light source by professor Alfano, who observed the phenomenon first time in 1970. The phase change induced by an intense ultrashort laser pulse propagating through a medium causes a frequency sweep within the pulse envelope, resulting in a well-defined temporal chirp. A look into the nonlinear mechanisms involved in producing such system and its potential applications are presented. Chapter 4 demonstrated wideband ultrashort pulse fiber laser sources using optical fibers and ultrashort pulse fiber lasers and a wavelength tuning range from 0.78 to 2.0 \( \mu \)m. The generation process and characteristics have been analyzed both experimentally and numerically. Chapter 5 provided an overview of experimental demonstration and theoretical understanding of lattice fabrication (including 1D lattices, 2D square lattices and ring lattices, and lattices with structured defects), as well as their linear and nonlinear light guiding properties. Discrete diffraction and self-trapping are

2
demonstrated in a variety of settings, including fundamental discrete solitons, discrete vector solitons, discrete dipole solitons, discrete vortex solitons, and necklace-like solitons. In addition, the formation of 1D and 2D lattices with single-site negative defects, and linear bandgap guidance in these structures were demonstrated. Chapter 6 discussed the second-order EO effect (Pockels), the third-order (Kerr) and thermo-optical effects in optical waveguides and their applications in optical communication. Chapter 7 presents a theoretical study and experimental data of beam combination using Stimulated Brillouin Scattering in improving upon the beam quality in optical fiber. The study includes both coherent and incoherent combination as well as two-beam phasing using the unique polarization characteristics of stimulated Brillouin scattering. Chapter 8 demonstrates a theoretical and experimental results of a double-functional interferometer, using holographic recording of a dynamic grating in CdTe:V crystal. The mechanisms involved were attributed to a slow electro-optical effect and a fast free-carrier grating. Chapter 9 represents the poling process on optical polymers to induce second and third order nonlinear optical effects. The chapter attributes the electro-optic effect in polymers to the presence of chromophore in the polymer matrix and explains the different approaches of incorporating the chromophore into the polymer matrix. It also explains the different poling methods and the poling mechanisms. Chapter 10 treats the effect of magnetic field and its role in nonlinear optics. It presents a set of experimental results, which prompt a reconsideration the role of magnetization in optics and predictions of optical magnetic resonance, negative permeability, and magnetic birefringence at optical frequencies. Chapter 11 describes the observations of Stokes and anti-Stokes emission of gold nano-particles as a three step process involving single-photon or three-photon excitation of electron-hole pairs, relaxation of excited electrons and holes, and emission from the electron-hole recombination. It also presents quantitative analysis of the experimental data. Chapter 12 explores the use of linear optics and the reliance on detection to design a number of optical logic gates that perform operations in the complex domain of linear optics and are converted to Boolean operations by the act of detection. These logic have no energy cost and the bandwidth is strictly limited by the electronic modulation and demodulation rate and can be integrated on chips with the electronics. Chapter 13 presents an answer to the important question: can the electric field of a light wave be assigned a definite polarity? In other words, can an optical field vector be more up than down? It also describes physical experiments and devices where this polar asymmetry is generated and detected and also connects the answer to the independently developed, Nobel Prize-winning technique of generating stabilized combs of mode-locked frequency components of light. Chapter 14 presents an excellent review of the chalcopryte materials and their potential as compact highly sensitive nonlinear optical sensors, of potential for many remote sensing devices. The chapter also touches on the integration of miniaturized photonic nonlinear bandgap structures, which enhances the nonlinearity and minimize problems associated with walk-off effects and outlines a theoretical analysis of nonlinear propagation in these structures. Chapter 15 presents the status of the ultimate device that can be attained in this 21st century through the photonic technology which is optical computing. The chapter lists the different components that might the optical computer will consist of and lists the most recent advances achieved and the substantial list of the recent literature on each component. It concludes with the obstacles to be overcome to build the system.
Contents

Chapter 1
Second and Third Order Nonlinear Optical Materials and Devices
Philip A Sullivan and Larry R. Dalton

Abstract
Introduction
Second Order NLO (Electro-Optic) Materials and Their Applications
Optimization of Molecular First Hyperpolarizability and Material Electro-Optic Activity
Optimization of the Optical Transparency of Electro-Optic Materials
Achieving Adequate Thermal Stability
Realization of Adequate Photostability
Stability in the Presence of High Energy Radiation
Synthetic Efficiency
The Cladding Problem
The Electrode Problem
Device Fabrication
Third Order Nonlinear Optical Materials
Acknowledgements

Chapter 2
Study of Soliton Stabilization in (D+1) Dimensions using Novel Analytical and Numerical Techniques
G.Nehmetallah and P.P. Banerjee

Summary
Outline
1. Introduction
2. Theoretical Background
   1. Pulse Propagation in Fiber: the 1-D NLS Equation
   2. Beam Propagation in Bulk media: Self-focusing Equation
   3. Nonparaxial Assumption in the NLS Equation
   4. Beam Propagation in saturating Nonlinearity
   5. Dispersion Management in D-dimensions
   6. Nonlinearity Management in D-dimensions
3. Hankel or Fourier Bessel Transform Methods
   Calculation of the Hankel Transform
4. Focusing Arrest Mechanism
5. Saturating Nonlinearity
6. Dispersion Management
   1. Variational Technique
   2. The 1-dimensional Case (D=1)
   3. The 2-dimensional Case (D=2)
Chapter 3
Supercontinuum generation and applications
Xiaohui Ni and R. R. Alfano

1. Introduction
2. Simple Theory of Self-Phase Modulation and Four-Wave Mixing
3. SC from Photonic Crystal Fiber
4. Optical Frequency Metrology
5. Atmospheric remote sensing
6. SC in optical communication
7. SC used for optical coherence tomography
8. Conclusion
9. Acknowledgements
10. References

Chapter 4
Wideband Ultrashort Pulse Fiber Laser Sources Using Nonlinear Effects in Optical Fibers
Norihiko Nishizawa and Toshio Goto

Abstract
1. Introduction
2. Wavelength Tunable Soliton Pulse Generation
   2.1 Physical Mechanism of Wavelength Tunable Soliton Pulse Generation
   2.2 Experimental Setup
   2.3 Characteristics of Wavelength Tunable Soliton Pulse
   2.4 Wavelength Tunable Two-Colored Femtosecond Soliton Pulse Generation
   2.5 Wavelength tunable soliton pulse and anti-stokes pulse generation
   2.6 Experiment based on another wavelength sources
3. Super continuum generation
   3.1 Widely broadened super continuum generation using highly nonlinear fiber
   3.2 High Quality Super Continuum Generation Using Soliton Pulse and Normal Dispersion Highly Nonlinear Fibers
4. Summary and future scope
5. References
Chapter 5
Optically-induced reconfigurable photonic lattices for linear and nonlinear control of light
Zhigang Chen and Jianke Yang

Abstract
1. Introduction
2. “Fabrication” of 1D uniform lattices and nonlinear discrete trapping
3. “Fabrication” of 1D defective lattices and linear bandgap guidance
4. “Fabrication” of 2D uniform square lattices and nonlinear discrete trapping
5. Discrete Fundamental Solitons
6. Discrete Vector and Dipole Solitons
7. Discrete Vortex Solitons
8. Discrete Soliton Trains and Necklace-like Solitons
9. “Fabrication” of 2D ring lattices and nonlinear discrete trapping
10. “Fabrication” of 2D defective square lattices and linear bandgap guidance
11. “Fabrication” of 2D ring lattices with a low-index core and its linear guidance
12. Summary
Acknowledgments
References

Chapter 6
Nonlinear Optics in Optical Waveguides and Its Applications
Xuejun Lu and Miao Li

1. Introduction
2. Electro-optic effect in optical waveguides
   2.1 Brief review of optical propagation in optical waveguides and index ellipsoid
   2.2 Linear electro-optic (EO) effect or Pockels effect
   2.3 Mach-Zehnder EO modulators
   2.4 Optical switch array based on EO effect
3. Third-order nonlinear (Kerr) effect and nonlinear optical resonators
   3.1 Brief review of the third-order nonlinear (Kerr) effect
   3.2 Optical intensity dependent phase delay and optical threshold gate
4. Thermo-optic effect and optical code-division multiple access (CDMA) encoder and match filter
   4.1 Brief introduction of thermo-optic effect in an optical waveguide
4.2 Optical CDMA and matching filters based on thermo-optical effect in optical waveguides

5. Summary and Acknowledgement
6. References

Chapter 7

Stimulated Brillouin Scattering Beam Cleanup and Combining in Optical Fiber
Timothy H. Russell, Brent W. Grime, Thomas G. Alley, Won B. Roh

Abstract
Introduction
Theoretical beam cleanup
Stokes Generation
Phase conjugation
Beam Cleanup
Experimental demonstrations
Beam Cleanup
Beam Combination
Two-Beam Phasing
Conclusions
References

Chapter 8

Confined nonlinear II-IV-V₂ waveguide structures for compact chemical and biological sensors
Nikolaus Dietz, and Frank Madarasz

Abstract
1. Introduction
2. Solid-State Molecular Sensor: Components
3. Confined Nonlinear II-IV-V₂ Waveguide Structures
   3.1. II-IV-V₂ Compound Semiconductors
   3.2. Confined Multifunctional Group II-IV-V₂ CP heterostructures
   3.3. The Growth of Confined Group II-IV-V₂ CP heterostructures
   3.4. Integration of photonic Bandgap Structures for diffraction and wavelength filters
4. Theoretical foundations
   4.1 Nonlinear Waveguides
   4.2 Coupling to Collector Surface
   4.3 Signal Processing
5. Summary
6. References
Chapter 9
Nonlinear emission of Au nanoparticles enhanced by Rhodamine 6G dye

M. A. Noginov, G. Zhu, and V. I. Gavrilenko

Abstract
1. Introduction
2. Ab initio calculation of electronic structure of Au
3. Absorption and emission of gold nano particles in methanol
4. Absorption and emission in the mixtures of rhodamine 6G dye and gold nano particles
5. Emission kinetics measurements
6. Summary
Acknowledgments
References

Chapter 10
Dynamic Holographic Interferometry with Double Functions – Optical and Electrical.


Abstract
1. Introduction
2. Theoretical Model
3. Step-like phase modulation
4. Fast response, based on Drude-Lorentz nonlinearity (DLN)
   4.1. Intensity modulation.
   4.2. Phase Modulation
5. Experimental Results at 1064 nm
6. Experimental Results at 1.15 μm
7. Discussion and Conclusion
Acknowledgements
References

Chapter 11
Poling of Nonlinear Optical Polymers

Michael D. Watson, Paul R. Ashley, Andrew J. Guethner, and Mustafa G. Abushagur

Introduction
Poling Methods
Poling Mechanisms
Single Layer Charge Distributions and Effects
Three Layer Waveguide Stack Charge Distribution.
Macroscopic Field Effects on Molecular Polarization
Electrostriction
Chapter 12
Optically-induced Magnetic Interactions in Nonlinear Optics

Abstract
1. Introduction
2. Theoretical Model
3. Electric and Magnetic Susceptibilities
4. Experiments
5. Discussion
6. Conclusions and Summary

Chapter 13
Relocating the Nonlinearity in Optical Logic
Lei Qian and H. John Caulfield

Abstract
Background
Complex linear optical logic
Binary Boolean logic functions and linear optical devices
Nonlinearity by detection
Conclusion
Acknowledgement
References

Chapter 14
The up and down directions of light’s electric field: are they different? – Quite often, YES!

Acknowledgment
References
Recent Advances in Photonic Devices for Optical Computing and the Role of Nonlinear Optics-Part II
Hossin Abdeldayem and Donald O. Frazier

Introduction
All-Optical Logic Gates
Adders
Optical processors
Optical Storage
Holographic Storage
Optical Interconnects
Spatial Light Modulators
Scope of Optical Materials
Conclusion
References