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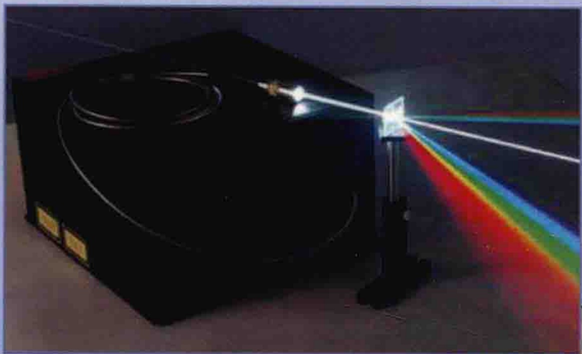
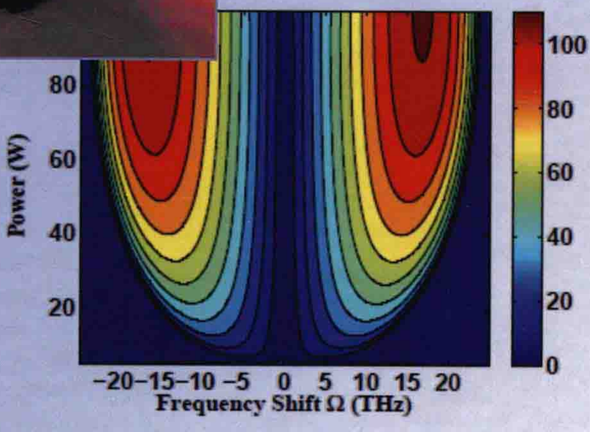
Odyssey of Light in Nonlinear Optical Fibers

THEORY AND APPLICATIONS





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Kuppuswamy PORSEZIAN
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Odyssey of Light in Nonlinear Optical Fibers

THEORY AND APPLICATIONS

Dr. K. Porsezian dedicates this book to his wife, P. Senthamizhselvi, and his sons, P. Gokul and P. Ragul.

Dr. R. Ganapathy dedicates this book to his parents, G. Ramanathan and Chithra Ramanathan, and his better half, Radhika Ganapathy.

Foreword

Dr. Akira Hasegawa *wearing the hat sent by Dr. V. N. Serkin for his 80^{th} birthday.*

Optical fiber waveguides provide very rich media for research and applications in modern optics because of the combination of small (group) dispersion and matching nonlinearity coupled with impressively small dissipation. Light waves in fiber waveguides propagate three-dimensionally but the energy or information represented by the envelope of the light waves propagates one-dimensionally in the direction of the fiber. Thus the dynamical evolution of information in fiber waveguides can be treated in one space dimension and time coordinates. The evolution equation including cubic nonlinearity and group dispersion (without loss), called the nonlinear Schrödinger equation, is integrable and the characteristic solution is given by (optical) solitons. In the more than 40 years since the discovery of optical solitons in fibers by Hasegawa and Tappert, impressive progress has been made both in theory and applications of solitons and related phenomena, much of which is summarized in this book.

The primary nonlinear response in fibers is the (electronic) Kerr effect, which increases the index of refraction with instantaneous response. However, its effect is very small; it induces a change in the dielectric constant on the order of 10^{-22} $(\mathrm{V/m})^2$, resulting in an increase of the index of refraction on the order of 10^{-12} for a lightwave with a power of 1 mW. Because the effect is so small, few people noticed the importance of this nonlinear effect. However, it should be recognized that this small change in the index of refraction appears in every wavelength of propagation, which is about 10^{-6} m. Thus it begins to become significant for a practical distance of propagation of a few kilometers even for a lightwave with a milliwatt level of power. Coupled with this, fiber (group) dispersion has been reduced and combined effects of nonlinearity and dispersion have become comparable. Furthermore, development of optical amplifiers has made fiber waveguides practically lossless. Thus the nonlinear Schrödinger equation is now regarded as the master equation for transmission of information in fiber waveguides. Since the nonlinear Schrödinger equation is integrable based on the inverse scattering transform of Zakharov and Shabat, information carried in nonlinear and dispersive optical fibers is robust like Fourier modes in linear systems. In a linear transmission system, the output signal in Fourier space is given by the product of the Fourier transform of the input signal and of the transfer function; thus the input signal can be precisely recovered by inverse Fourier transformation of the product. The integrability of the nonlinear Schrödinger equation in principle warrants the same procedure and all the information should be recoverable, even when the transmission system is nonlinear, where Fourier information is destroyed. More concretely, the complex eigenvalues (both amplitude and phase) in the inverse scattering transform are preserved in the transmission, like Fourier components in a linear system, and thus should in principle be recoverable with proper reverse transformation of the output signal. In this regard coherent transmission is possible in nonlinear optical fiber; namely, using a soliton for one bit of information, although it is robust, is a waste of the channel capacity. Only recently this fact began to be recognized and used for ultra-high speed transmission. This will truly open a new era of nonlinear communication systems where the Fourier transform becomes irrelevant. In this regard, the soliton-based transmission concept in optical waveguides has just begun its new paradigm.

Soliton-related phenomena in optical fiber waveguides have wide applications, including modulational instability, pulse compression and generation of a continuous spectrum and the like. New theoretical developments of integrability of the modified nonlinear Schrödinger equation, including nonautonomous cases by Serkin et al.,* have opened up a new paradigm of the soliton concept to nonlinear quantum field theory in addition to a new information transfer concept. In this respect, the soliton concept in fiber waveguides is still on the way to full blossom.

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Professor Emeritus
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*V. N. Serkin, A. Hasegawa, and T. L. Belyaeva. Phys. Rev. Lett. 85 (2007)

Preface

Optical fiber technology has emerged as one of the prominent technologies of the century as it encompasses a wide range of applications—from medical optics to all optical information processing. Extensive research carried out in the field of optical fiber communications has revolutionized the fiber optic industry by paving the way for the discovery of new laser materials and optical fibers with new designs and configurations. In particular, after the invention of lasers, the role of nonlinear optical effects and their applications in different nonlinear materials have been extensively used by the scientific community as well as industry. Among different nonlinear materials, optical fiber is a widely used medium for many important applications, including ultra-high-speed communication networks, pulse compression, erbium-doped fiber amplifiers, etc. Further, the study of optical solitons in nonlinear materials has also attracted a lot of attention due to its potential applications in many branches of science and technology, including the generation of supercontinuum sources through soliton fission and modulational instability. The previously mentioned ventures, in turn, have opened the door to new technical possibilities and exploration of new opportunities for the commercialization of fiber optic deliverables. As an example, appropriate dispersion engineering of highly nonlinear photonic crystal fibers has resulted in the development of a special class of dispersion compensating fibers that exhibit interesting phenomena such as supercontinuum generation. As the supercontinuum light source is characterized by its ability to provide ultra-wide band and high coherence, its applications have spread over a wide range of fields, encompassing telecommunication, medical imaging, spectroscopy, optical frequency metrology, gas sensors, etc.

Conventional silica core photonic crystal fibers are the best contenders for telecom applications as the carrier wavelength can be shifted to 1.55 micrometers where loss is at a minimum. Some important applications, such as industrial welding, surgery, sensing, etc., demand higher operating wavelengths. In these cases, photonic crystal fibers having core materials that provide minimum losses at higher operating wavelengths are usually preferred. This has opened the gateway to study the performance of potential core materials such as chalcogenide glasses, heavy metal fluoride glasses, polycrystalline materials, etc., in order to explore the possibilities of obtaining optimal higher operating wavelengths. Special classes of photonic crystal fibers that have hollow cores are most sought for potential applications in the fields of medicine, telecommunication, gas cells, remote sensing, etc., as they provide much smaller absorption, nonlinearity, and material dispersion than their solid-core counterparts. Due to the high performance characteristics of hollow-core photonic band gap fibers, a plethora of opportunities have been opened up for minimally invasive laser surgery. Other than the conventional microhole photonic crystal fibers, macrohole microstructured fibers, whose air holes or other cladding structures that extend in the axial direction have been studied extensively as they can be manufactured easily, thereby leading to cost-sensitive applications. No wonder that multinational companies such as Alcatel-Lucent, ATT, etc., have invested heavily in optical fiber technology. This calls for a conglomeration of the core concepts and applications of nonlinear optical fiber technology where the unique optical properties, ranging from optical solitons to optical rogue waves, are contemplated, thereby acting as a tribute to the odyssey of light.

This is a collection of breakthrough research work that portrays the odyssey of light from optical solitons to optical rogue waves in nonlinear optical fibers, exploring the very frontiers of light-wave technology. Furthermore, this book also provides a simple yet holistic view on the theoretical and application-oriented aspects of light, with special focus on the underlying nonlinear phenomena. The reader is exposed to some of the latest advances in nonlinear optical fiber technology, ranging from optical solitons to optical rogue waves. In a nutshell, the contents of this book are as follows: The basics of nonlinear fiber optics are discussed at length in Chapter 1. In Chapter 2, the dynamics of electromagnetic pulse propagation in nonlinear waveguides are discussed in detail. Employing the coupled mode dynamics approach, nonlinear propagation in various continuous and discrete systems encompassing parity-time optical coupled systems, binary arrays, dual-core photonic crystal fiber and fiber amplifiers are discussed in detail in Chapter 3. The possibility of the existence of Ablowitz–Ladik rogue wave hierarchies is investigated at length in Chapter 4. In Chapter 5, a detailed theoretical study on modulational instability in relaxing saturable nonlinear optical media is carried out. The conditions for the occurrence of various types of modulational instabilities in two twin-core fibers that are governed by coupling coefficient dispersion are discussed in Chapter 6. By employing the generalized non-isospectral Ablowitz–Kaup–Newell–Segur (AKNS) hierarchies, the nonlinear dynamics of solitons in various nonautonomous nonlinear and dispersive physical systems, whose properties are completely determined by hidden symmetry parameters, are studied extensively in Chapter 7. Various types of soliton propagation nonlinear fiber optics that encompass isothermic-, hypothermic-, hyperthermic- and hybrid solitons are discussed in detail in Chapter 8. In Chapter 9, a compact review of theoretical results that throw light on the prediction of a generic method in supporting stable spatial solitons in dissipative optical media is carried out. The frontiers of mode locking using fiber lasers are explored in detail in Chapter 10, mainly aided by the development of advanced statistical tools on one hand and the technological improvements of the characterization methods and devices on the other hand. An extensive study on matter wave solitons and other localized excitations pertaining to Bose–Einstein condensates in atom optics is carried out in Chapter 11. An in-depth study based on symmetric soliton propagation in nonlocal nonlinear media where pertaining to linear Gaussian and periodic potentials is carried out in Chapter 12. The theoretical and experimental procedures for the generation of dual radiation in suspended photonic crystal fibers are studied extensively in Chapter 13. In Chapter 14, the theory and the experiment of parabolic similariton propagation in nonlinear optical fibers and their subsequent applications that encompass pulse amplification, coherent continuum for optical communications, ultrafast all-optical signal processing and spectral compression are studied extensively. Chapter 15 discusses the theoretical concepts, experimental techniques, and applications of Brillouin scattering. Various aspects of nonlinear effects and their ensuing propagation occurring in optical metamaterials owing to forward and backward wave interactions are discussed in detail in Chapter 16. Backpropagation, an effective technique to compensate for deterministic dispersive and nonlinear effects in optical fibers, is discussed in detail in Chapter 17. Chapter 18 dwells on the concept of eigenvalue communication, a powerful nonlinear digital signal processing technique that paves the way to overcome current limitations of traditional communications methods in nonlinear fiber channels. The feasibility of the eigenvalue demodulation scheme based on digital coherent technology by throwing light on the experimental study of the noise tolerance of the demodulated eigenvalues is the subject of Chapter 19. Finally, Chapter 20 discusses in an extensive manner the various quantum field theory analogue effects occurring in binary waveguide arrays, plasmonic arrays, etc., and their ensuing nonlinear wave propagation.

We hope that this book serves as a commemoration of the International Year of Light (2015).

Kuppuswamy Porsezian
Ramanathan Ganapathy

Acknowledgments

First and foremost, the editors acknowledge Dr. Akira Hasegawa, the father of soliton communication systems, for his valuable support and advice throughout the preparation of this book. We are thankful to Dr. M. Lakshmanan, the father of nonlinear dynamics in India, for his constant encouragement. We also express our sincere gratitude to all the contributing authors of this book for having charted the road map for *Odyssey of Light in Nonlinear Optical Fibers*, and without whose valuable contributions this book would not have materialized. The editors acknowledge Dr. Ajoy Ghatak and Dr. K. Thyagarajan for providing permission for the front cover from the Fianium, United Kingdom. We also acknowledge the Fianium, United Kingdom, for the same. CRC Press deserves a special acknowledgment of their editorial and production departments for the valuable support rendered by their capable team.

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Last but not least, the editors acknowledge the Almighty for clearing all the obstacles in their odyssey in the preparation of this book.

Editors

Dr. K. Porsezian

Kuppuswamy Porsezian, PhD, earned his MSc degree in physics from the University of Madras, Chennai, India, in 1985, and his PhD degree in physics from Bharathidasan University, Tiruchirapalli, India, in 1991. After working as a research scientist with the SERC, Department of Science and Technology (DST), Government of India Project, in 1993, he joined the Department of Physics, Anna University, Chennai, India as a lecturer. He is currently a professor with the Department of Physics, Pondicherry University, Puducherry, India. He has published more than 175 papers in international journals and edited five books on optical solitons. His current research interests include solitons and modulational instability in nonlinear fiber optics, self-induced transparency solitons, nonlinear pulse propagation in periodic structures, metamaterials and photonic crystal fibers, and integrability aspects of nonlinear partial differential equations.

Dr. Porsezian received the Indian National Science Academy (INSA) Young Scientists Award of the Year 1995, the Deutscher Akademischer Austauschdienst (DAAD) Post-Doctoral Fellowship from 1995 to 1997, the Anil Kumar Bose Memorial Award by the INSA in 1998, the Sathya Murthy Memorial Award of the Indian Physics Association for the Year 1998, Junior and Regular Associateship Award from 1995 to 2002, the All-India Council of Technical Education Career Award for Young Teachers from 1998 to 2001, the University Grants Commission Research Award from 2004 to 2007, and the Department of Science and Technology Ramanna Fellowships from 2006 to 2009. He was a program advisory committee member (2004–2012) and is a member of the Fund for Improvement of Science and Technology Infrastructure (FIST) (2008–present) of the DST, Government of India. He was also a member of the New Millennium Indian Technology Leadership Initiative committee of CSIR, received an incoming fellowship from the European Union to visit Gdansk University, Poland (2010). He was elected a fellow of the Indian Academy of Sciences Bangalore (2012) and the National Academy of Sciences, Ahmadabad (2013).

Dr. R. Ganapathy

Ramanathan Ganapathy, PhD, earned a MSc degree in physics from the University of Hyderabad in 1993 and the M.Phil. in physics from Cochin University of Science and Technology in 1996. He pursued his research at the same university and earned his PhD degree in physics in 2003. He worked as a post-doctoral fellow for three years in the CSIR-sponsored project Nonlinear Dynamics of Femtosecond Pulse Propagation in Nonlinear Fibers at Pondicherry University. Presently he is a senior assistant professor at the Centre for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA University, Tamilnadu, India.