Ritesh Kumar Chourasia
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Bragg Fibers

From Optical Properties to Applications

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I would like to dedicate this book to honor my parents (Mom and Dad), who planted the seed of knowledge, kindness, and human values in my mind and nurtured it. I bow my gratitude to my beloved wife and my heartbeat (lovable family members) for their continuous love and support. —Ritesh Kumar Chourasia

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Foreword

Recent Nobel prizes stand a testimony to the fact that optics and photonics are contributing greatly to the development of societies around the world. The invention of lasers in 1960 provided an unprecedented impetus to the field, and progress in this field has been very rapid leading to developments in fiber optics and optical communication, nonlinear optics, quantum optics, optical sensing, super-resolved imaging, and many other areas. The UN recognized these contributions with the declaration of 2015 as the Year of Light and Light-based Technologies, following with the declaration of May 16 as the International Day of Light. Academic and commercial activities, in this field, have also seen unprecedented growth over the last few decades. In particular, optical fibers, particularly specialty fibers, have provided a platform for many developments including sensors, nonlinear optics, and high power lasers. In this respect, fibers with some periodic variation in structures have become particularly interesting from the point of view of many applications. These include fiber gratings, photonic crystal fibers, and Bragg fibers. Some of these structures are inspired by structures in nature. This book is concerned with Bragg fibers which in the most basic form contain periodic or nearly periodic layers of high and low refractive indices in the radial direction. These have many unusual properties and require a somewhat involved mathematical framework to analyze. Since the initial proposal in late 1970s, a great amount of research and development work has been done in over four decades. This book is a commendable effort to describe and analyze these developments.

The book provides a comprehensive overview of the latest advancements in multi-layered, multi-material Bragg fibers spanning nine chapters. The first few chapters cover analytical techniques, theorems, and commonly used mathematical techniques. Next three chapters discuss various optical characteristics of these fibers and how these can be tailored. These are then followed by two chapters on applications of these fibers in sensors and other devices. The final chapter briefly includes some aspects of nonlinear wave propagation through Bragg fibers. The book thus presents a clear and coherent progression of the theoretical formulation, modeling, optical features, and practical advancements of multilayered, multi-material Bragg fiber. The authors have vast experience of research in the area and significant part of the book has grown out of their work. This gives the depth and clarity to the presentation.

This book, probably the first on this topic, would serve as a valuable reference and research monograph for both beginning and experienced researchers in the fields of theoretical and experimental optics and photonics with a particular interest in specialty fibers. This book would be very useful for graduates and postgraduate students in physical sciences who are interested in conducting research in the field of photonics.

This book is a welcome and valuable addition to the educational literature on the subject and would benefit students in science and engineering in learning about Bragg fibers and their applications.

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Preface

Total internal reflection, a well-known optical phenomena, is utilized to guide light in conventional optical fibers (COFs). In order to account for this optical phenomena, the core material of the COFs must possess a refractive index (RI) that is greater than that of the cladding material. The benefits of these COFs compared to traditional waveguides such as microwave devices and two-wire transmission lines are manifold: they provide a wider bandwidth with lower attenuation, exhibit resistance to electromagnetic (EM) interference, and possess characteristics of being lighter, more flexible, safer, and more secure. However, COFs do have disadvantages. The high refractive index (RI) of the core material leads to several unwanted consequences, including doubly degenerate fundamental modes, losses in the cladding and material, unidirectional propagation of light, strong nonlinearity, and geometrical and material dispersions. Therefore, these significant limitations of COFs can be overcome by innovative Bragg fibers (BFs) that have a hollow/air core. The publication of the influential study by Yeh and Yariv in 1976 ignited a surge of interest in the field of BFs research and continues to captivate researchers' focus to this day. The Bragg gratings (BFs), consisting of periodically arranged cylinders with varying refractive indices (RIs), play a crucial role in guiding the light through the waveguide by utilizing multiple Bragg reflections. The phenomenon of Bragg reflection enables the transmission of light through a hollow core. These devices have minimal nonlinearities, are not affected by polarization or birefringence, do not experience Fresnel reflections at the end of the fiber due to coupling in air, and are not influenced by material or cladding loss because over 98% of the mode is confined in the air rather than the high-index silica material. The hollow core of Bragg fiber facilitates the entrance or passage of biological solutions or chemical gases, rendering it an optimal platform for chemical or biological sensors. A solitary TE or TM mode can spread through BFs, and other means, due to the fact that the basic modes are not degenerate. Furthermore, the biological roots of the arrangement of cylindrical concentric periodic patterns in the shape are well established. The botanical fruit *Margaritaria nobilis* has an outward form resembling a cylindrical structure with layers. This form of construction is inspired by a multilayer artificial structure that possesses a photonic band gap (PBG), which may be further adjusted by applying mechanical pressure to its surface. The construction of a functional Photonic Band Gap (PBG) is significantly influenced by the periodic nature of the Bragg's Factor (BF) structure. The form, dimensions, arrangement, and coating material of the multilayer periodic structure together influence the effective width of the photonic bandgap (PBG). By employing photons as the means of transmitting information, instead of the less efficient electrons, the telecommunications sector will undergo a revolutionary transformation, resulting in a significant enhancement in the capacity and speed of intricate communication networks. However, in order to utilize the technological potential of BFs effectively, it is crucial to have the capacity to adjust and modify their characteristics dynamically. This book examines the transmission of electromagnetic waves in hollow-core Bragg fibers for the purpose of sensing and filtering. The proposed structure features a centrally hollow core, which is surrounded by cladding consisting of alternating layers with high and low refractive indices. The regular occurrence of alternate claddings with high and low refractive index in Bragg fibers results in the formation of a photonic bandgap. Researchers utilize this photonic bandgap (PBG) as a signal in sensing applications. In order to enhance the sensing capabilities, they employ cladding layers that possess a short photonic bandgap (PBG) and a low refractive index (RI) contrast. In order to improve the sensing capabilities, the structure of the BFs includes a defect layer that acts as a Fabry–Pérot resonator. When the defect is located in the appropriate photonic bandgap region, a prominent peak is noticed. This defect peak might potentially be utilized to create a narrow-band optical filter or a detection signal. An intelligent material placed within the cavity exhibits an electro-optic effect when subjected to an external electric field, resulting in the displacement of the defect peak within the analyzed photonic bandgap. The resonant state within the BFs structure fluctuates as a result of mechanical strain induced along the cavity. Therefore, the utilization of an external field allows for further adjustment of the suggested BFs structure. Furthermore, the proposed framework offers a wide range of potential applications in the future. These include the development of optoelectronic noses that utilize Boolean-olfaction and multi-material multifunctional BFs capable of visual perception, auditory reception, sensory detection, and communication. Additionally, the framework might enable the creation of square-shaped multi-material BFs, among other possibilities. The primary goal of this book is to ascertain the sensing applications of electromagnetic wave propagation characteristics in boundary fields with a defect layer. The book is organized into nine chapters.

Chapter 1 of this book explores the relationship between the physical characteristics, visual appearance, and chemical dependence of natural photonic systems. It demonstrates how this understanding may be applied to create new artificial photonic systems for various applications in photonics and sensing. Our strong motivation compels us to engage in natural photonics research, resulting in the development of specialized templates for photonic technology layouts. Here, we examine the findings of a study on the hierarchical optical structure present in the grain shell of *Margaritaria nobilis* fruits. Additionally, it resulted in the creation of pioneering Bragg reflected light BFs, which disturb a coaxially stacked structure within the individual cells of the grain's outer tissue layers. This bioinspired BFs structure has two technologically exploitable properties for modifying light and color. Wavelength-selective light scattering occurs due to the presence of both nanoscale regularity and microscale cylindrical symmetry, resulting in light being scattered in various directions. The artificial bio-inspired structure discussed in Chap. 1 is a multilayer-wrapped structure made up of two different refractive index phases and a hollow center. The artificial system simplifies certain complications seen in the natural structure, such as the elliptical shape of the fruit cell and the cross-section inside the periodic layers. Despite these simplifications, the artificial system maintains a similar scale and underlying optical interaction to its natural counterpart.

Chapter 2 explores the utilization of standard fiber drawing processes to construct BF structures from tiny preforms. However, the ability to draw materials into multilayer fibers is rather restricted. In order to reduce the occurrence of fractures at the interfaces of materials when operating at high temperatures, it is necessary for the pre-made material combinations to possess a suitable refractive index contrast and thermal expansion coefficients that fit the lattice structure. The chapter also explores an alternative approach to producing fibers at room temperature. This process involves using several types of organic polymers and inorganic materials, which provide a wide range of optical and mechanical qualities. Unlike thermally drawn fibers, these fibers are not restricted to having longitudinal symmetry along their axis. Additional dielectric materials utilized in fiber production encompass thermoplastics, such P.S. polystyrene and PMMA, which stands for polymethyl methacrylate. The rolling approach has been employed to incorporate thin metal films into non-stretchable fibers. Spray coating and blade coating are established industrial methods that may be used in roll-to-roll manufacturing and should be considered as potential possibilities for producing large-scale bilayers. During the process of film deposition, it is possible to modify the specific thicknesses of the two films in the first bilayer. Consequently, the position of the fibers' reflection band in the spectrum may be readily modified. These fibers display significant reflection over a limited range of wavelengths determined by the periodicity of the multilayer structure. This reflection is accompanied by a decrease in transmission, resembling the optical characteristics of the tropical fruit.

Chapter 3 employs the transfer matrix technique, the asymptotic method, and the Galerkin method to provide a theoretical description of the structure of BFs. In addition, it explores how the transfer matrix method may be modified to calculate reflection at interfaces, single slabs, and multilayer cylindrical stacks, as well as the dispersion optical characteristics of Bragg filters. This approach is more straightforward compared to the often employed Chew's method due to its reduced number of High/Low RI layers. It has been shown that in order to produce accurate results, the criterion of asymptotic approximation must be satisfied. The T.E. refers to the acronym for "Technology Engineering." The terms "H-Polarization" and "T.M." refer to certain modes of electromagnetic wave propagation. The study focuses on analyzing the E-Polarization modes and exploring the bandgap.

Symmetric birefringent fibers possess a core with a low refractive index that is hollow and surrounded by a cladding that is periodic and free from any geometric or symmetry imperfections. Chapter 4 of the book focuses on the characteristics of hollow-core BFs, including their propagation and dispersion properties. These BFs are designed to have high refractive index (RI) cladding contrast combinations and are optimized for minimal loss at the visible window wavelength of 632.8 nm. The boundary matching methodology has been employed to establish a correlation between the incident and transmitted light waves utilizing the most suitable transfer matrix technique. The photonic band gap (PBG) obtained in high contrast cladding Bragg fiber (HCCBF) has a significant magnitude, hence necessitating fewer periodic cladding layers to get a flawless PBG with complete reflection (100%). The width and position of photonic bandgaps (PBGs) are greatly influenced by the angle at which the electromagnetic wave strikes, specifically the route that the incoming light takes. In sensing applications, the sensitivity of the Bragg fiber may be assessed by measuring either the width or the spectrum shift of the PBG.

In Chap. 4, we observe that the high-contrast cladding hollow core BFs exhibit a wider photonic bandgap (PBG) with a significantly high full width at half maximum (FWHM). Thus, the performance of these setups is considerably affected in sensing applications. In Chap. 5, we recommend for achieving the smallest full width at half maximum (FWHM) of the sensor signal. To attain the lowest full width at half maximum (FWHM), one might utilize a defect layer or disrupt the symmetry of the Bragg periodic cladding. In this chapter, we construct and theoretically assess hollow core BFs with a defect layer for the design window at a wavelength of 632.8 nm. The connection between the initial and final fields has been stabilized by ensuring that the electric and magnetic fields are in alignment at different interfaces, as explained extensively in Chap. 3. The formulae for reflectance and transmittance have been discovered as well. A Bragg periodicity in the tested wavelength range results in the formation of a flawless photonic bandgap (PBG). The presence of a defect layer inside Bragg periodicity results in the emergence of a minor defect peak within the ideal photonic bandgap zone. The frequency at which the cladding layers repeat influences the full width at half maximum (FWHM) of this defect peak. The position and displacement of the defect peak are also influenced by the beam's angle of incidence and the refractive index of the core material. Consequently, rather than utilizing the full photonic bandgap (PBG) as a detecting signal, it is preferable to focus on the defect peak.

Chapter 6 focuses on the efficient design and manufacturing of BFs that are made from many materials and have multiple functions. The chapter specifically explores the use of preform-based technologies for this purpose. The fiber optic devices are composed of chalcogenide semiconducting glass and an insulating polymer bilayer. In addition, there are four metal electrodes available for the fabrication of novel integrated devices. Furthermore, it investigates the electrical and optoelectronic capabilities of metal-semiconductor-insulator BFs in order to fulfill the required device functionalities. The utilization of Bragg optical resonators with external surface reflectors on fiber resonators has also been investigated for hollow BFs core bases. Self-monitoring beamforming systems have the potential to be extremely important for transmitting high amounts of optical power. These systems may be used in various industries, such as industrial and medical sectors. Chapter 6 provides a comprehensive analysis of the application of narrowband Bragg photodetectors, which utilize amorphous chalcogenide glasses to accurately detect a wide spectrum of light wavelengths. This book chapter further investigates the coveted and unique use of surface-emitting lasers utilizing BFs.

Previously, we have observed that BFs possess a structure characterized by a hollow core, rendering them well-suited for applications in bio/chemo sensing. The hollow core of the BFs structure functions as a flow cell, capable of containing biological solutions or facilitating the movement of chemical gasses. Chapter 7 of the book describes the creation of a successful optofluidic BFAS adulteration sensor device configuration, which incorporates a geometric flaw. The objective of this setup is to enhance and supervise the impurities in a temperature-dependent ratio of hydrated mono-alcohol fuel, considering various weather conditions. The PPBG has a limited spectral sensitivity profile (SSP) as a result of a geometric flaw in the design of the BFAS sensor device. This defect exhibits a high level of sensitivity to variations in the refractive index (R.I.) of the fuel-filled core during hydration. The newly designed optofluidic BFAS device configuration demonstrates a substantial improvement in P.P. The metrics of the current sensors are superior to those of previous similar sensors, mainly because of the smallest full width at half maximum (FWHM) of the single scattering peak (SSP). The BFAS device configuration has achieved a peak sensitivity of 1057.3 nm/RIU under all weather conditions. The sensitivity of this sensor exceeds that of the surface plasmon resonance optic sensor in detecting hydrated mono-alcohols, but only under static temperature conditions. Reducing the full width at half maximum (FWHM) of the sensor signal profile (SSP) in this configuration improves the detection accuracy (D.A.) and quantification precision (Q.P.), since both metrics are inversely linked to the FWHM.

Chapter 8 focuses on an analysis of a high-contrast optical inline filter that possesses dual electrical adjustment capabilities. This optical inline filter is specifically developed for low-power multiwavelength LASER applications. It is positioned in close proximity to the PMMA cavity, alongside a single-crystal ferroelectric PMN-PT. An efficiency of almost 90% has been attained in the photonic bandgap (PBG) under investigation by manipulating the angle of incidence and applying direct current (DC) voltages, resulting in the transmission peak via this structure. To regulate the thickness of the cavity, it is important to provide an external voltage to the PMN-PT single crystal. Consequently, the PBG structure may be modified correspondingly. This technology has a broad range of application, spanning up to 129 nm. This is achieved by utilizing the reversible domain switching capabilities of PMN-PT layers, which requires a little voltage modification of around 20 V. Hence, the optical inline filter created by BFs shows great potential for various multiwavelength LASER applications, fulfilling the demands of present-day situations such as optical instrument testing, optical communications, fiber sensor systems, optical signal processing, modern telecommunications, and sensors multiplexing industry.

In Chap. 9, we have examined the non-linear transmission of optical pulses with a duration of several hundred femtoseconds in solid-core Bragg fibers. An investigation was conducted on the impact of pulse-width, peak power, soliton order, and higher order dispersion on the evolution of sech pulses in the nonlinear regime. Theoretical models indicate that the early widening is mostly influenced by the effects of group velocity dispersion (GVD) and self-phase modulation (SPM), whereas the creation of dispersive waves becomes apparent after a specific length of the fiber. The solid-core Bragg fibers (also known as DDBFs) can be created using the widely used MCVD technology. This technology is both reproducible and economically viable once it is standardized. It provides a suitable platform for studying nonlinear optical effects at sub-micrometer wavelengths, taking into account various dispersion characteristics.

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(Dr. Aavishkar Katti)

Contents