Frontiers in Guided Wave Optics and Optoelectronics

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Preface

I have great pleasure in introducing this e-book “Frontiers in Guided Wave Optics and Optoelectronics” under the new series Advances in Lasers and Electro Optics being published by IN-TECH Publishers. Guided wave optics and optoelectronics are at the heart of optical communications, optical signal processing, miniaturization of optical components, biomedical optics, defense applications, and so on. The most recent recognition of the importance of this subject has been acknowledged through the conferral of the Noble Prize in Physics for 2009 to Dr. Charles Kao “for groundbreaking achievements concerning the transmission of light in fibers for optical communication". The charter of the Noble Prize states that it is given to “ …. who shall have conferred greatest benefit on mankind”. Optical communication in the last two decades has revolutionized the way information is transferred in terms of instant transmission as well as access especially the Internet. Optical fiber networks are now taken for granted regardless of the scale of access, be it inter-city, inter-continental, metro or local. Transmission loss in silica fibers has been reduced to nearly the lowest possible limit, dispersion of signals in a telecom grade fiber can be highly controlled to a level where signals are transmitted over long distances without any significant impairment, and nonlinearity-induced distortions can be reduced drastically through appropriate fiber design. With all these remarkable achievements, it appeared for a while in the mid-1980s that there would be no further scope for research in optical fibers. However it turned out that new demands arose for specialty fibers, in which dispersion and nonlinearity could be tailored to achieve transmission properties, which are otherwise impossible in conventional fibers. Around this time, the concept of photonic crystals (PhC) was put forward, which eventually led to the development of microstructured optical fibers (MOF), which are also referred by some as photonic crystal fibers (PCF).

Chapter 1 forms the subject matter of specialty optical fibers such as large negative dispersion coefficient fibers, which are known to serve as dispersion compensating fibers. Inherently gain flattened erbium doped fibers, which do not require any gain flattening filters as a cost effective solution for the metro optical networks are also described in this chapter. The so-called photonic bandgap guided fibers, which fall within the class of microstructured fibers, constitute a completely new type of fiber waveguides, whose functional principle for light guidance and confinement is totally different from that of conventional fibers. In certain forms, these fibers are capable of guiding light in an air core thereby enabling the propagation of light with ultra low loss. As a corollary, these fibers can also serve as a conduit for high-energy pulses without causing any material damage within the fiber or impairing the signal due to nonlinearities induced at high powers. Microstructured fibers also form a versatile platform for generating supercontinuum (SC) light, which is a highly spatially coherent, intense broadband light with imminent applications that range from biomedical imaging and engineering to laser development and the generation of stable frequency combs.

Chalcogenide glass-fibers, which form another example of application-specific specialty fibers, are described in chapter 2. Fibers drew from As-S-Se-like glass systems exhibit large nonlinearities. The authors, who are from a leading group in the US on this topic, have highlighted the utility of such fibers for building up compact Raman as well as Brillouin amplifiers, SC light generators in the near and mid-infrared wavelength regions, fast optical switches, optical regenerators for high speed telecommunication systems, efficient slow light realization and many more aspects.

Measurements on nuclear radiation response of a variety of commercially available radiation hardened fibers are described in chapter 3. In nuclear environments, optical fibers are often employed for data collection as hybrid sensors and transmission of the same to a remote date processing center, as well as light-guides for control and diagnostics. Through detailed studies on the gamma, beta and neutron irradiation of these fibers, the authors have described the role and mechanism behind the formation of different types of colour centers as a result of the irradiation. These colour center formations are attributed to molecular bonding between different basic constituents at the atomic level. Such studies are important from the point of view of choosing material systems in the fabrication of radiation-hardened fibers.

Chapter 4 (which is a collaborative effort by authors from Russia and Scotland) describes programmable all-fiber techniques (e.g. linearly chirped fiber Bragg grating) for the synthesis and control of fast (pico to sub-pico second) temporal optical pulses for applications in nonlinear optical switching and wavelength conversion devices. The control of short, parabolic flat-top optical pulses is also important for self-phase modulation-induced supercontinuum generation experiments. Such optical signal processing techniques are important in e.g. ultrahigh-bit-rate optical communications, coherent control of atomic and molecular processes, and generation of ultra-wideband RF signals.

In chapter 5, the authors deal with the topical phenomenon of *slow light* (SL), which has garnered enormous attention in recent years. SL essentially refers to the significant slowing down of the group velocity of light in a medium near its resonance i.e. at frequencies where propagating light resonantly interacts, e.g. for gain or absorption, with atoms or molecules. Slow light has several potential applications as delay lines, optical buffers, equalizers etc, especially from the optical communication perspective. Unfortunately the topic essentially remained an academic curiosity for a long time because at a resonance the gain or absorption of light in the media is far too strong to be fruitfully fully exploited for device realization. In late 1990s it was shown that through *nonlinear* resonance interactions, such as in *stimulated Brillouin scattering (SBS)*, group velocities could be brought down to few tens of meters per second because $\mathrm{d}n/\mathrm{d}\omega$ could be large and yield sharp resonances. The authors argue that realizing this effect in an all-fiber form, e.g. as a delay line, is all the more attractive because as a device, this could be seamlessly integrated into an optical fiber network through techniques such as splicing. The authors make a detailed study of SBS and the physical mechanism by which a Stokes pulse can be slowed in an optical fiber.

In chapter 6, optical amplification characteristics of Bismuth doped glass and fibers in the O-band spanning from 1260 nm to ~1360 nm are described. Optical amplification through erbium doped fibers in the wavelength band spanning the C- and L-band across 1530 ~ 1610 nm has matured as a present technology. However, since the demand for bandwidth is ever-increasing, utilization of additional potential amplifier bands of high-silica fibers for wavelength division multiplexed transmission is always attractive. Though Fiber Raman amplifiers and Praseodymium-doped glass fiber amplifiers could work at the O-band, their gain bandwidth is rather limited. Bismuth doped fiber amplifiers can potentially offer a much wider gain bandwidth, which is the topic of study of this chapter. Since zero dispersion wavelengths of conventional fibers like ITU specified G-652 fibers (example, SMF-28 of Corning Inc.) fall within the O-band, development of wide band amplifiers (as well as lasers) for this band is very attractive because it would amount to adding more transmission bandwidth and could complement fiber amplifiers already studied for the C-, L-, and S- bands. One important finding of their studies is the necessity of co-doping with Aluminium for achieving broadband luminescence at the infrared wavelengths when pumped with commercially available 810 nm high power laser diode.

New demands for broadband wireless in access networks, radar related data processing, hybrid fiber radio (HFR), mm wave and THz generation systems, etc have given rise to a new application-specific research area of optical fibers known as Radio-over-Fibre (RoF), which forms the subject matter of chapter 7. This subject area is also often referred to as microwave photonics, in which a radio signal typically in the millimetre wave band is transmitted through optical fibers employing laser sources and electro-optical devices. HFR, in some sense, is similar to hybrid-fibre coaxial (HFC) network, in which a combination of digital and analog channels are distributed in the last mile through coaxial cables with the main difference that in HFR, the 'last-mile' distribution is done wirelessly. The authors state that in the RoF technology the required RF signal processing functions in one shared Central Office and then optical fibers are used to distribute the RF signals to the remote access units (RAU), which make this approach very cost effective. This enables the incorporation of advanced network features such as dynamic allocation of resources.

As mentioned in chapter 1, nonlinear aspects of microstructured specialty fibers (also referred to as photonic crystal fibers) is exploited to dramatic effect for broadband SC light generation. These fibers also offer engineerable dispersion profiles, which facilitate control over the nature of the generated SC light. SC generation has been known to result from soliton fission processes as well as Raman effects and some phase matching phenomena, which occur on these fibers under the right conditions. The dynamics and interactions between solitons as well as the phenomenon of dispersive wave generation are dealt with in chapter 8 and provide insight into how propagating femtosecond pulses generate new frequencies. This topic is also extensively investigated experimentally by deploying the so-called sum frequency generation (SFG) X-FROG (Cross correlation frequency resolved optical gating) technique, which is a *time-spectral* visualisation technique. Besides conventional MOFs, the authors have also investigated SC from soft glass like SF_6-based extruded MOFs, in which nonlinearity could be much stronger than high-silica glass and they could show quite remarkable agreement between theory and experiment.

In chapter 9, the authors describe three varieties of dispersion compensating devices, which play important role in the generation, amplification and propagation of dispersion-free femtosecond pulses. Various such devices include chirped mirrors, grating and prism pairs and are discussed in this chapter, out of which grating pair-based dispersion compensation approaches have been discussed in greater detail, which is of critical importance for the field of ultra-fast optics.

Dispersion tailored photonic crystal or microstructured fibers form the subject of study in chapter 10. Though there is some overlap of the discussions with those discussed in chapter 1, this chapter provides greater details on dispersion characteristics of MOFs. The introduction contains a concise review of the state-of-the-art of various fiber designs. The authors present their analysis of the dispersion profiles of photonic band gap (PBG) fibers including solid-core and hollow-core photonic crystal fibres, whose periodicity is modified by applying resonant Gires-Tournois interferometric (GTI) resonant layers around the core, which induces a frequency-dependent phase shift of the light. This concept is then utilized to design Bragg fibers with the layers immediately adjacent to the core having parameters that are distinct from the rest of the high and low index layers in the periodic cladding, which form the GT layers. The same concept is then extended to an all-glass PCF as well as a hollow-core Bragg fiber and a hollow-core PCF with honeycomb cladding for tailoring their dispersion properties.

Chapter 11 is concerned with a detailed study on the origin and influence of refractive index change (RIC) induced due to population inversion in resonant fiber structures such as Ytterbium (Yb)-doped fiber lasers, which operate in the 1 μm spectral region. The results presented in this chapter indicate that far-resonance electronic transitions in the UV rather than near-resonant IR transitions are responsible for the RIC. By extending their arguments, the authors propose exploiting this effect to develop a simple all-fiber solution for coherently beam combining rare-earth-doped fiber amplifiers through active phase control in an all-fiber spliced configuration.

In chapter 12, current research and applications of periodically poled lithium niobate (PPLN)-based optoelectronic devices, which include tunable wavelength filters, polarization controllers, electro-optical and various switches are reviewed. Since lithium niobate is used extensively for configuring integrated optical waveguides, this study, in principle, can be extended to waveguide geometries. Theoretical analyses and designs of integrated optical wavelength-selective switches (with potential operating speeds of *a few tens of picoseconds or faster)* in the form of a cascaded Mach-Zehnder interferometer (MZI) are discussed in the subsequent chapter (Chapter 13). Cascaded MZI's are an excellent candidate for configuring integrated optical wavelength interleavers due to their inherent strong wavelength selectivity. In chapter 13, the authors propose a combination of Raman waveguide amplifiers integrated in the arms of the first stage MZI and the integration of an attenuator in one of the arms of the second stage MZI as a means to achieve control of light amplitude through stimulated Raman scattering. The authors also describe an alternative architecture for such a switch in which three Raman amplifiers are placed in the lower arms of a three-stage cascaded MZI. The efficiency of its switching operation is verified through computer simulation by employing a finite difference beam-propagation-method.

Chapter 14 discusses nonlinear integrated optical device platforms based on high-index doped-silica materials. Often referred to as silicon photonics, this platform offers a compromise between the linear optical properties of single-mode fibers and those of semiconductors and other nonlinear glasses. In particular, measurement techniques to characterise the linear and third order nonlinearities, with specific applications to parametric four wave mixing (FWM) are described. Potential applications such as narrow line width, and/or multi-wavelength sources, on-chip generation of correlated photon pairs, as well as sources for ultra-low power optical hyper-parametric oscillators are also projected.

Advances in inscription of waveguides and micro/nano-photonic devices through the use of high-power, focused femtosecond laser pulses, generally referred to as femtosecond micromachining, are reviewed in chapter 15. In this chapter, the authors highlight the interactions between a suitable material (typically glass) and short pulses that result in permanent changes in the physical, chemical and optical properties of the material on a sub-micron scale. State-of-the-art femtosecond laser sources, machinable materials, and some of the current applications for this type of technology are also reviewed. Interestingly this technique has been used to produce phase masks, which are essential for fabricating wavelength selective fiber devices such as in-fiber Bragg gratings. This technology can be used to realize high aspect ratio, micron-scale channels as microfluidic lab-on-chip devices such as for measuring a specific particle to particulate sorting and counting. Due to the high point density that can be achieved through the spatial confinement of the femtosecond pulse-material interaction, this technology has been also used in high density data storage and retrieval applications, for creating sub-micron features in polymers through polymerization, producing photonic crystal structures and even for fabricating medical stents. The authors state that the industrialisation of micromachining processes will be of great significance in the future of solar cell and flexible organic light emitting diodes (OLEDs) or manufacturing techniques which require highly localised and fast creation of complex, machinable patterns.

Magneto-optical materials for integrated optical waveguides, which form the topic of chapter 16, are attractive for optoelectronics because of their unique characteristics like non-reciprocity and retention of memory. The most common example of one such component, which is required in an optical communication network, is an optical isolator, which is invariably used as an integral component in a fiber amplifier to prevent it from lasing. The authors of this chapter report on the growth of (Cd,Mn)Te waveguides on GaAs substrate for realizing magnetooptical integrated optical isolator with a high isolation ratio of 27 dB, a low optical loss of 0.5 dB/cm, and a high magneto-optical figure-of-merit of 2000 deg/dB/kG over a 25-nm wavelength range. They have also utilized the magnetization reversal of nano-magnets through spin-polarized photo-excited electrons for realizing non-volatile, high-speed optical memory. Metal clad magnetooptical waveguides have also been described in this chapter.

The subject of the next chapter 17 is based on hollow optical waveguides, known as Bragg reflectors, for integrated optics. These waveguides confine light by Bragg reflectors oriented transversely to the direction of propagation. A widely tunable Bragg reflector is introduced which demonstrates on-chip polarization control for adjustable compensation of polarization mode dispersion (PMD). Owing to a weak dependence of air on temperature, the phase delay suffered by the light confined in hollow core waveguides (which have been introduced in Chapter 1), is nearly temperature-insensitive, which is of significant advantage in waveguide-based sensors. By incorporating MEMS-based actuators on either of the multilayer Bragg mirrors, the air gap between the mirrors can be tuned to achieve tunable propagation characteristics of such waveguides. Chapter 18 is also devoted to Bragg gratings in which the grating is located exclusively along the longitudinal direction of a fiber's core – the so-called Fiber Bragg Grating (FBG) - with a focus on increasing the operating temperature ranges of these FBGs. The authors refer to these devices as regenerated fiber gratings, which can withstand temperatures in excess of 1200°C. These gratings have a number of potential applications, which include their role in monitoring furnace temperatures in various situations, and their utility as a component in high peak power fibre lasers. In the following chapter 19, optical deposition of carbon nano tubes (CNTs) onto optical fibers to realize CNT-based fiber devices is described including fundamental properties of CNTs, their fabrication, and CNT-based optical devices. Utility of CNT as a passive mode-locker, or as a saturable absorber for ultrashort pulse generation is well known for sometime now. Authors developed a method, which enables area-selective deposition of CNTs only onto the core region of an optical fiber end. Evanescent coupling between CNTs and propagation mode of a microfiber is one way to realize a polarization insensitive CNT device. The authors demonstrate a passively mode-locked fiber laser having optically deposited CNTs (to serve as saturable absorber) circumscribing a microfiber, which's tapered (realized through heat and stretch method) waist was ~ 6 μm.

Thulium (Tm^{3+}) doped fibers initially attracted attention from the point of view of their use as fiber amplifiers at the S-band. Chapter 20 describes high power Tm^{3+} fiber lasers and their utility as pump for chromium doped ZnSe (Cr^{2+}:ZnSe) lasers. In Tm^{3+}-doped fiber lasers, output at the mid-infrared wavelengths ~ 2 μm is realizable, which is extremely important from the point of view of laser microsurgery due to high absorption by water in this spectral region. Thus these lasers could provide high-quality laser tissue cutting and welding in biomedical optics besides potential applications in environment monitoring, LIDAR, optical-parametric-oscillation (OPO) pump sources, and so on. Authors discussed a variety of double clad fiber structures to configure Tm^{3+} doped fiber lasers. This longest chapter spread over 70 pages in the book contains details of several issues e.g. spectroscopy, fabrication, scalability, nonlinear optical effects, wavelength tenability, self-pulsing, Q-switched operation, etc. of Tm^{3+} fiber lasers.

In chapter 21, development of ~ 2 μm wavelength emitting lasers in the form of crystal lasers, fibre lasers and semiconductor lasers are discussed. For the crystal and fiber lasers, authors focus on thulium and holmium doped systems, in which output powers close to 1 kW and slope efficiencies of up to 68 % have been reported. The chapter also describes latest improvements of GaSb-based laser diodes and ends by indicating their potential applications in spectroscopy, sensing, surgery, and material processing.

Chapter 22 focuses on the design and realisation of photonic crystal (PhC)-based micro resonators for lasers. In view of the versatility afforded by PhCs, optical properties of such resonator can be manipulated without almost any restrictions. Two different schemes for designing PhC laser resonators were discussed by the authors. The first one uses a bulk active region, which is surrounded by a PhC-mirror and the second type uses the PhC directly as the gain medium. Incorporation of PhCs allows for a full control of the dispersion relation of a resonator, and hence enables newer designs of resonators. Surface plasmonic waveguides, in which the active semiconductor region is sandwiched between two metallic layers of gold, were also used to realize THz quantum cascade lasers.

Ceramic lasers form the subject matter of chapters 23 and 24. Due to their short fabrication period and being mass-producible, the cost of ceramic laser materials could be much lower than that of single crystals. Furthermore, no complex facilities and critical techniques are required for the growth of large sized ceramics. At a low doping concentration, efficiency of a diode-end-pumped Nd:YAG ceramic laser was found to be higher than that of a Nd:YAG single crystal laser. A high-power (6.8 W) tunable Yb:YAG ceramic laser with a slope efficiency as high as 72% has been demonstrated at room temperature. A diode pumped passively mode-locked Yb:YAG ceramic laser was also demonstrated for the first time by the authors in chapter 23. Broad tunability in the spectral range from 994.35 to 1098.87 nm and from 992.52 to 1110.83 nm in two different cases at room temperature were also obtained in such Yb:YAG ceramic lasers. In chapter 24, polarization properties of laser diode pumped micro-chip Nd:YAG ceramic lasers is presented. The author of this chapter points out that ceramic lasers, which consist of randomly distributed single crystals surrounded by grain boundaries, are interesting for studying lasing properties in random media. Observed segregations into multiple local-modes due to field interference effect among the local-modes and the associated variety of dynamic instabilities that occur in laser diode-pumped Nd:YAG ceramic samples were discussed.

Chapter 25 is concerned with surface-emitting circular Bragg lasers. Surface-emitting lasers have attracted attention because of their salient features such as low-threshold current, single-mode operation, and wafer-scale integration. Their low-divergence surface-normal emission also facilitates output coupling and packaging. Vertical Cavity Surface Emitting Lasers (VCSELs) though available commercially, their single-modedness and good emission patterns are guaranteed only over a very small mode area (diameter of ~ μm). Attempts to further increase the emission aperture have failed mostly because of the contradictory requirements of large-area emitting aperture and single modedness. From this perspective, circular Bragg lasers could circumvent this problem. This chapter contains a comprehensive and systematic theoretical study on the surface-emitting Hankel-phased circular Bragg lasers in various geometries. According to the authors, these lasers should find applications in ultra-sensitive biochemical sensing, all-optical gyroscopes, and coherent beam combining, and as high-power, high-radiance sources in communications and display technology.

The integration of optical and wireless mode of communication in access networks is the subject matter of chapter 26. It essentially implied the convergence of two conventional technologies - radio frequency (RF) for wireless access in the last tens of meters and optical fiber for wired transmission across long-range links. RoF techniques have been discussed in an earlier chapter. Authors here argue that service providers for next-generation access networks are expected to offer end users greater choice, convenience and variety in an efficient way, which would require delivery of voice, data and video services with mobility feature to serve the fixed and mobile users in a unified networking platform. Ultra uncompressed HD Video with (UHDV) 7680 x 4320 pixels (33 Mega pixels) plus 22.2 sounds (24 channels in three layers) would require 40 GB/s or higher data speed. The chapter contains details of a variety of enabling technologies to accomplish such convergence including results from a test bed.

Photonic crystal (PhC)-based optical multiplexers (MUX)/demultiplexers (DMUX) are discussed in chapter 27, in which the authors initially dwells on definition and functional principle of PhCs including role of defects in periodic structures of this kind for realizing optical components and devices. Two different geometries of PhC were studied in detail as MUX/DMUX of 1310/1550 nm wavelengths. According to them integration of PhC with planar lightwave circuits would play an important role in integrating photonic components and devices to an optical network.

Maximum transmission distance in a fiber optical community antenna TV (CATV) system is still limited by RF parameters. A number of techniques like split-band schemes, light-injection and dispersion compensation have been applied to extend this bottleneck. Authors of chapter 28 discuss these techniques with the target to make a cost effective fiber optic CATV system, for which they argued that it is important to combine fiber optical CATV systems with other applications, e.g. Internet access and WiMAX services.

Active optical alignment of optoelectronic components in any optical communication system is an important issue especially in high-speed optical communication systems such as 10 Gb/s or higher. In most situations, passive techniques are employed. Chapter 29 describes a bi-directional MEMS-based optical beam steerer as an active solution to minimize such technological issues. This was achieved through use of a silicon optical bench containing a set of micro-machined silicon components comprising of the substrate, RF feed-through, hermetic sealing and optical alignment functions.

As the editor, I feel extremely happy to present to the readers such a rich collection of chapters authored/co-authored by a large number of experts for this book covering the broad field of guided wave optics and optoelectronics from around the world. It was indeed a monumental task to edit such a large volume. Most of the chapters are state-of-the-art on respective topics or areas that are emerging. Several authors narrated technological challenges in a lucid manner, which was possible because of individual expertise of the authors on their own subject specialties. I have no doubt that the book would be useful to graduate students, teachers, researchers, and practicing engineers and technologists and they would love to have it on their book shelves for ready reference at any time.

I thank Professor Vedran Kordic for inviting me to edit this book, which was a delightful experience for me in view of the ocean of knowledge and information that is contained in each chapter. In fact Professor Kordic contacted individual chapter lead authors. On behalf of Prof. Kordic and the publisher of this e-book, I would thank all the contributors for their scholarly contributions. Finally I would like to thank my daughter Parama Pal, presently with the Wellman Laboratory of Photomedicine at the Harvard University Medical School in Boston, USA for helping me with the composition of the preface and editing of the book.

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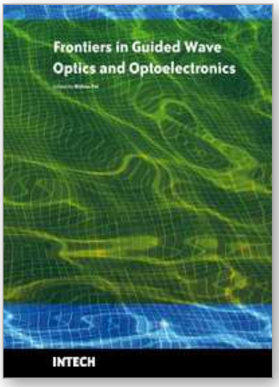

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