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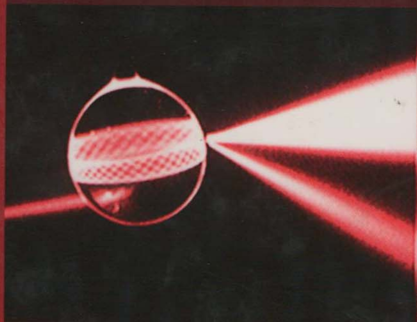

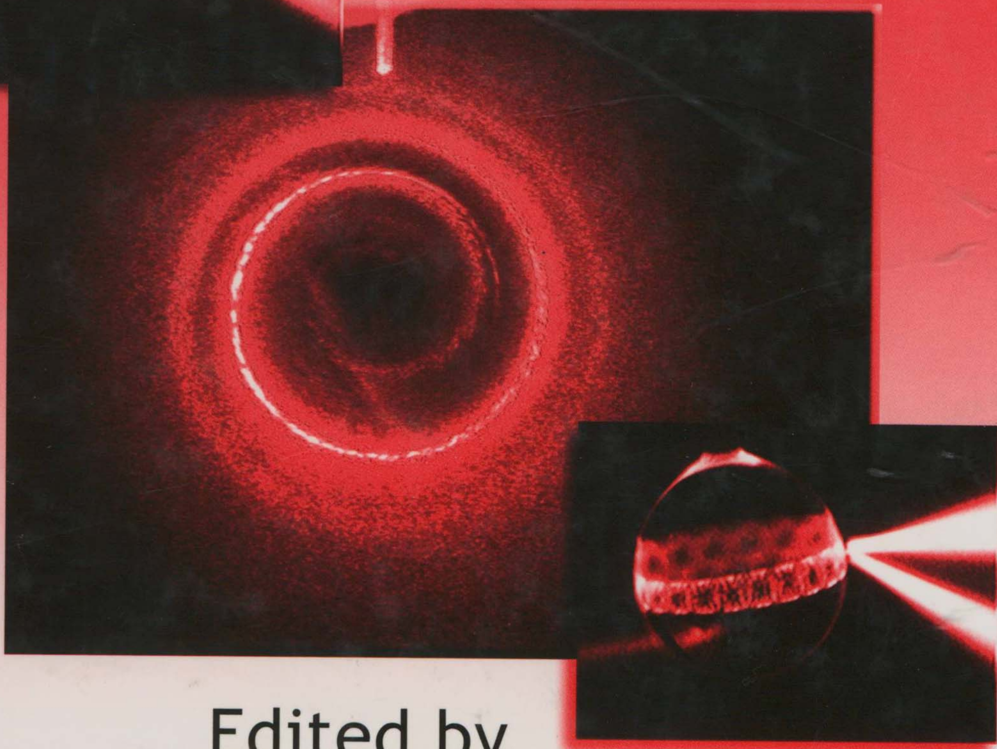

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Preface

The race for compactness and scalability of optical and photonic devices calls for the development of efficient micro- and nano-optical elements. The optical resonators are important here because they can be used in the optical signal processing systems as modulators, filters, delay lines, switches, sensors, and so on. The number of the different types of resonators increases every day, and the basic research of their properties is gradually and steadily substituted with applied research. Such practical issues as efficient packaging and robust coupling, as well as integration of the resonators into complex optical systems, become especially important when one tries to bridge the gap between the fundamental research and practical implementation.

There are many scientific books and reviews discussing the properties of optical microresonators, and I believe that at this stage it is important to have a collection reviewing the basic directions in the development of the practical applications of the microresonators, which is my goal with this book. Though it is practically impossible to cover the whole field with several contributions, I hope that this collection will provide readers with the flavor of the applied studies in the field and will convince them that systems containing microresonators will soon become as common and widespread as electronic devices containing quartz oscillators. I also hope that this book will attract the attention of a general audience dealing with R&D in broadly defined physics/electrical engineering areas to the fascinating world of the microresonators. The chapters are written by brilliant scientists and engineers working in the field and can be understood by any graduate student in the field.

Traditional mirrored optical resonators are utilized in all branches of optics where, for example, multiple recirculation of optical power is required to maintain laser oscillation, to increase the effective path length in spectroscopic or resolution in interferometric measurements, and to enhance wave mixing interactions. Crucial properties of the resonators, such as high quality (Q) factor and finesse, can be achieved with the highest reflectivity and low-loss mirrors. Despite their versatility, these resonators have remained fairly complex devices. They are prone to vibration instabilities because of relatively low-frequency mechanical resonances. Stability and small modal volume are of great importance for practical applications; however, miniaturization of conventional Fabry–Perot resonators is either complicated and expensive, or yields rather low Q-factors.

This book contains several reports on the progress in the rapidly growing field of monolithic micro- and nano-resonators. Such resonators do not have localized mirrors as such. The light is confined inside these resonators due to their morphology. The monolithic resonators are characterized by the unique combination of properties unreachable in other resonator structures. They have tiny volumes along with huge finesse and Q factors. The modal spectrum of the resonators can be efficiently engineered. These properties make the resonators extremely efficient in multiple applications.

The first chapter in this book, authored by Takasumi Tanabe et al. (NTT Corporation, Japan), is devoted to photonic crystal-based resonators (nanocavities). Among various microresonators, photonic crystal nanocavities have the smallest mode volume (V) and nearly the highest Q/V value. High Q/V devices are attracting considerable attention because they enable multiple quantum and nonlinear optics applications. Recent progress on these ultrahigh-Q photonic crystal nanocavities is also discussed in the first chapter.

Various designs of photonic crystal nanocavities, fabrication and the characterization technologies are reviewed. In addition, various applications like light buffering, slow light propagation, all-optical switching, and bistable memory operation are discussed by the authors.

The second chapter, authored by Charles Santori et al. (Hewlett-Packard Laboratories, USA), is devoted to the discussion of applications of a particular type of distributed feedback microresonators called "pillar microcavities". These microcavities are well suited for efficient coupling of dipole emitters to a single mode in free space and thus are suitable for generation of photons on demand. The design, fabrication and characterization of single-photon devices based on single InAs quantum dots coupled to pillar microcavities formed from AlAs/GaAs distributed-Bragg-reflector mirrors are described in this chapter. Several applications including quantum cryptography and entanglement formation through two-photon interference are presented. Future applications that could be developed as the devices improve are also discussed.

Chapters 3 through 11 deal with the resonators in which the closed trajectories of light are supported by a variety of total internal reflection in curved and polygonal transparent dielectric structures. The circular optical modes in such resonators, frequently called whispering gallery modes (WGMs), can be understood as closed circular beams supported by total internal reflections from the boundaries of the resonators. High values of Q-factor can be achieved in WGMs of very small volume, in certain cases as small as cubic wavelength, with appropriately designed dielectric interface and with use of transparent materials. Applications of the microresonators made of various materials, including silicon, fused silica, fluorite, lithium niobate, and polymers are discussed in these chapters.

These resonators have cylindrical, spherical, spheroidal, toroidal, ring, and other shapes and topologies. When the reflecting boundary has high index contrast, and radius of curvature exceeds several wavelengths, the radiative losses, similar to bending losses of a waveguide with high refractive index contrast, become very small, and the Q factor of the resonators becomes limited only by and material attenuation scattering caused by geometrical imperfections (e.g. surface roughness).

Fabrication of the open dielectric resonators can be simple and inexpensive, and they lend themselves to integration. The unique combination of very high Q (as high as 10^{11}) and very small volume has attracted interest in the applications of the resonators in fundamental science and engineering. Small size also results in excellent mechanical stability and easy control of the resonator parameters. The authors describe applications of the resonators for filtering and modulating light, for detecting chemical and biological substances. Various lasers and oscillators based on the resonators are also discussed.

Namely, Lute Maleki et al. (OEwaves Inc., USA) discuss application of crystalline WGM resonators in filtering and laser stabilization in Chapter 3. Applications of polygonal-shaped microdisk resonators are studied in Chapter 4, authored by Andrew W. Poon et al. (The Hong Kong University of Science and Technology, People's Republic of China). Applications of electro-optic polymer ring resonators for millimeter-wave modulation and optical signal processing are reviewed by William H. Steier et al. (University of Southern California, USA) in Chapter 5. Chapter 6, authored by Melanie Lebental et al. (Ecole Normale Superieure de Cachan, France), is devoted to the discussion of properties of organic micro-lasers. Practical applications of optical microfiber loop and coil resonators are described in Chapter 7 by Misha Sumetsky (OFS Laboratories, USA). Chapter 8, authored by Xudong Fan (University of Missouri, Columbia, USA), deals with optofluidic ring resonator biological and chemical sensors. An application of crystalline microresonators for fabrication of a non-electronic wireless receiver with immunity to damage by electromagnetic pulses is introduced in Chapter 9 by Bahram Jalali et al. (the University of California, Los Angeles, USA). Properties and applications of cavity enhanced optomechanics are studied in Chapter 10, authored by Tobias Kippenberg (Max Planck Institut für Quantenoptik, Garching, Germany) and Kerry Vahala (California Institute of Technology, USA). Generation of optical frequency combs in optical microresonators and applications of the combs are described in Chapter 11, authored by Oliver Arcizet et al. (Max Planck Institut für Quantenoptik, Garching, Germany).

The last two chapters are devoted to the theoretical discussion of the properties of long chains of coupled microresonators. Though the fabrication of such chains is still problematic because of technological immaturity, the theoretical studies shed light on the problems and phenomena one needs to expect once the chain fabrication becomes feasible. Chapter 12, written by Jacob Khurgin (Johns Hopkins University, USA), is focused on the two most important factors limiting the performance of linear and nonlinear optical devices based on coupled resonator structures. These factors are, respectively, dispersion of loss and dispersion of group velocity. Chapter 13, authored by Shayan Mookherjea (University of California, San Diego, USA), deals with linear and nonlinear localization of light in chains of nearly identical resonators.

I hope that this book will help accelerate the already rapid pace of the research and developments in the exciting field of the applications of optical microresonators. I would like to thank the authors for their contributions making this book a success. This book would not have been possible without the assistance of my colleagues Lute Maleki, Anatoliy Savchenkov, and Vladimir Ilchenko. I am also thankful to Allyson Beatrice for her assistance.

Andrey B. Matsko

Editor

Andrey B. Matsko (MS, 1994 and PhD, 1996, Moscow State University, Russia) has been a principal engineer with OEwaves Inc. since 2007. He joined the company after six year employment as a senior/principal member of technical staff at Jet Propulsion Laboratory (JPL) and four year post-doctoral training at the Department of Physics, Texas A&M University. He has numerous publications in the field and holds several patents. His current research interests include, but are not restricted to, applications of whispering gallery mode resonators in quantum and nonlinear optics, and photonics; coherence effects in resonant media; and quantum theory of measurements. He is a member of the *Optical Society of America* and a member of the *Program Committee of Photonics West: Laser Resonators and Beam Control Conference.* He received JPL's Lew Allen Award for excellence in 2005.

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