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# Optical Microresonators

## Theory, Fabrication and Applications

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# Preface

In writing this book we sought to describe some of the important aspects and applications found in the wonderful world of optical microresonators. Of course we tell it from our respective points of view. These vantage points have been clearly biased by the specific roads we took during our investigations. We only hope that it does not detract from the ideas and information collected in this research monologue. We would never admit to perfection and cannot claim mathematical rigor in the theoretical chapters nor detailed process recipes in the chapter on fabrication. These circulating fields and their interactions have kept us busy and entertained both conceptually and in the lab for the better part of a decade. When we started out in this field, there was no textbook to consult. It is our hope that students and researchers entering this field now have such a guide.

We dedicate this effort to Erika, Priya, Rhea, Uma, Dalia, and Mariam.

# Acknowledgments

John E. Heebner graduated first in his class with a B.E. in engineering physics from Stevens Institute of Technology, Hoboken, NJ, in 1996. He then conducted graduate studies at the Institute of Optics, University of Rochester, where he received a Ph.D. in optics in 2003. Dr. Heebner's doctoral research on the topic of nonlinear optical effects in microring resonators was carried out under the supervision of Prof. Robert W. Boyd. Much of the material for this book derives from those investigations supported by the National Science Foundation (NSF) and the Defense Advanced Research Projects Agency (DARPA). Dr. Heebner is currently employed as a Senior Optical Scientist by Lawrence Livermore National Laboratory in Livermore, CA.

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Rohit Grover completed his B.Tech. in engineering physics from the Indian Institute of Technology Bombay, Mumbai, in 1997. He then received both an M.S. and Ph.D. in electrical and computer engineering from the University of Maryland, College Park, in 1999 and 2004, respectively. Dr. Grover's research on semiconductor optical microresonators was carried out primarily at the Laboratory for Physical Sciences, College Park, MD. This book draws, in part, on Rohit's work while at the University of Maryland, where he received support from a Graduate Research Assistantship (1998-2000), Distinguished Graduate Research Assistantship (2000-2003), and an IEEE-LEOS Graduate Student Fellowship (2001). Dr. Grover is currently a Senior Process Integration Engineer at

Intel Corporation, Hillsboro, OR, where he is studying die-package interactions for the 45-nm node.

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Tarek A. Ibrahim received B.S. and M.S. degrees in electrical engineering from Cairo University, Giza, Egypt, in 1996 and 1999, respectively. He then joined the Laboratory for Physical Sciences, University of Maryland, College Park, as a graduate student and completed his Ph.D. in 2004. His research while at the University of Maryland was on the topic of all-optical signal processing using nonlinear semiconductor microring resonators. Dr. Ibrahim received the University of Maryland Graduate Fellowship in 1999 and the Distinguished Electrical and Computer Engineering Graduate Research Assistantship in 2001. He is currently a Senior Process Integration Engineer at Intel Corporation.

Tarek would like to thank the staff of the Laboratory for Physical Sciences. In particular, he thanks his advisors, Prof. J. Goldhar and Prof. Ping-Tong Ho, and his colleagues, Philippe Absil, Kuldeep Amarnath, John Hryniewicz, Rohit Grover, Vien Van, Ken Ritter, and Marshall Saylors. He also thanks his family for their support throughout his Ph.D. and during his professional life. He also thanks his advisor at Cairo University, Prof. Adel El-Nadi, for his great support and continuous encouragement.

# Contents

# 1. Introduction

## 1.1 Optical Microresonators

Optical microresonators have demonstrated great promise as fundamental building blocks for a variety of applications in photonics. They can be implemented for such diverse applications such as lasers, amplifiers, sensors, optical channel dropping filters (OCDFs), optical add/drop (de)multiplexers (OADMs), switches, routers, logic gates, and artificial media. For brevity and in keeping with their current usage in the literature of this field, we specialize the term "microresonators" and generalize the term "microring resonators." We use these terms interchangeably in this book to refer to any of a number of compact geometries that support cyclically propagating modes that close on themselves in a ring-like geometry.

One particular embodiment of a microring resonator consists of an ordinary waveguide that channels light in a closed loop. But in general, the loop can take the form of other closed shapes, such as a disk, racetrack, or ellipse. In the case of a ring, the microresonator is simply a curved waveguide closed onto itself forming a resonant cavity that supports both transverse and longitudinal (here azimuthal) modes. The confinement and channeling of light in this closed geometry, however, does not require an inner dielectric boundary. This is evidenced by the existence of optical "whispering gallery" modes in a microdisk or microsphere resonator. Placement of a microresonator near one or two waveguides (Fig. 1.1) enables access to modes of the resonant cavity. In this particular arrangement, the resonant modes are accessed through evanescent coupling — a phenomena analogous to tunneling in solid-state physics. Component wavelengths of an optical signal channeled in a waveguide are resonant with the cavity if its (effective) circumference supports an integer number of wavelengths. For these spectral components of the signal, an increased circulation of intensity can build up in the resonator. The presence of a second waveguide coupled to the ring enables extraction of the resonant, circulating signal. Component wavelengths that do not resonate with the ring bypass it altogether. Thus, at their most fundamental level, microring resonators act as a spectral filter and a temporary compressor of energy density. These properties are not unique to microring resonators.

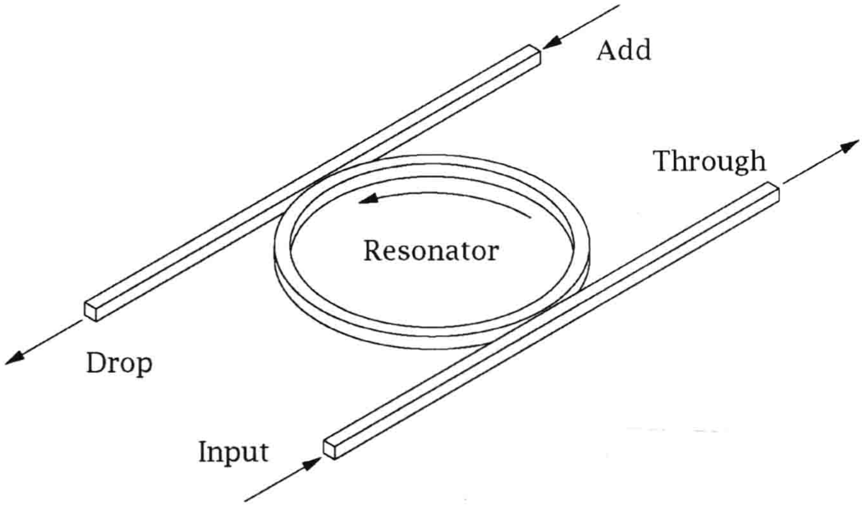


**Fig. 1.1.** Schematic of an optical microring resonator add/drop filter.

Rather, they are common to all resonant cavities such as the well known Fabry–Perot resonator.

Although functionally similar to Fabry–Perots, microring resonators offer several advantages. First, their planar nature is naturally compatible with monolithic microfabrication technologies. Second, high finesse operation does not require multilayer or distributed Bragg reflectors but is rather achieved by increasing the gap widths of evanescent couplers. Third, because the equivalent injected, transmitted, and reflected waves occupy spatially distinct channels, the need for costly Faraday circulators is eliminated. Fourth, for the same reason, although there is only one natural way to sequence arrays of Fabry–Perots (into multilayer stacks) three altogether new possible arrangements for arrays of resonators are enabled that differ qualitatively in many ways.

The small scale-size of microresonators currently achievable by state-of-the-art fabrication methods is important for many reasons of which we highlight two. First, because the propagation velocity of light is of the order of a few hundred $\mu$m per ps in most optical materials of interest, high bandwidths (GHz to THz) are naturally attainable. Second, their small dimensions allow the integration of many devices on the same chip, enabling high-level functionalities such as ultrafast all-optical signal processing at a heretofore unrealized compact scale. Because of these inherent advantages, the very large-scale integration (VLSI) of high-bandwidth photonics may rely on optical microresonators. In the next section, we offer our perspective on how microresonators came to be important components in the photonic toolbox.

## 1.2 Historical Perspective

The "whispering gallery" effect was analyzed (with wave approaches) as early as 1910 by Lord Rayleigh [1]. His analysis of the channeling of acoustic waves by the dome of St. Paul's cathedral in London is a precursor to similar methods applied to electromagnetic waves. Ring and disk resonators for electromagnetic waves have since been implemented in microwave applications starting in the early 1960s. In the optical domain, integrated ring resonators were proposed in 1969 by Marcatili at Bell Labs [2].

The first guided optical ring resonator was demonstrated by Weber and Ulrich in 1971 [3–5]. Weber and Ulrich's device consisted of a 5-mm-diameter glass rod ($n = 1.47$) coated with Rhodamine-6G-doped polyurethane ($n = 1.55$), for a resonator circumference of 31.4 mm. Light was coupled in and out of the resonator with a prism. By pumping the polymer with light from a $N_2$ laser ($\lambda = 337.1$ nm), they obtained laser operation. The next relevant demonstration was by Haavisto and Pajer in 1980 [6]. Their device was the first to incorporate integrated bus waveguides made with a doped polymethyl methacrylate (PMMA) film on quartz substrate. A significant feature of their work was that the device was fabricated without lithography by using direct-writing with a 325-nm He–Cd laser. Although they demonstrated low-loss waveguides and rings, the ring was quite large (circumference 28.3 cm). Nevertheless coupling to the ring was via evanescent coupling to integrated bus waveguides, and the basic idea had been established.

In 1982, Stokes, Chodorow, and Shaw [7] demonstrated the first optical glass fiber ring resonator, operating at $\lambda = 632.8$ nm. Fibers unfortunately, do not lend themselves to compact integrated optics; their resonator had a circumference of 3 m. Between 1982 and 1990, numerous groups demonstrated integrated ring resonators based on glass. Early efforts used ion-exchange from $AgNO_3$, $KNO_3$, and similar compounds that modify the index of the glass, to make the waveguide core. Walker and Wilkinson demonstrated a ring resonator with silver ion-exchanged glass in 1983 [8] (circumference 3.1 mm, operating at $\lambda = 632.8$ nm), as did Mahapatra and Connors in 1986 [9,10] (circumference 4.1 mm, operating at $\lambda = 632.8$ nm). Honda, Garmire, and Wilson demonstrated a ring resonator with potassium ion-exchanged glass in 1984 [11] (circumference 25.1 cm). A related effort by Naumaan and Boyd in 1986 [12] used CVD phosphosilicate glass films. Other efforts used Ti-exchanged $LiNbO_3$ (Tietgen, 1984 [13]), and proton-exchanged $LiNbO_3$ (Mahapatra and Robinson, 1985 [14]). Tietgen's work is especially significant as it represents the first demonstration of a tunable ring resonator. Instead of a circular ring, he used a waveguide loop with two 3-dB couplers. His device used electro-optic tuning, had a circumference of a little over 24 mm, and operated at $\lambda = 790$ nm.

Since the early efforts outlined above, there have been numerous works in various doped and undoped silica-based glasses [15–25], Si- ($Si_3N_4$, SiON, $SiO_2$) [26–37], and polymers [38–41] in the past decade. Many of these studies have reported multiring filters, temperature-insensitive operation and so on. Oda's work with $TiO_2$-doped silica-glass rings represents the first demonstration of serially cascaded rings, with increased free spectral range over single-ring devices. Rabiei's work with polymer rings represents the first passive and active polymer ring resonator.

Microresonators constructed in III–V semiconductors began "seeing light" in the early 1990s. Several groups demonstrated optically pumped microdisk lasers in both GaInAsP-InP and III–Nitrides using the whispering-gallery; the smallest reported disks had circumferences of $\sim 15\ \mu m$ [42–50]. Most of these early efforts did not incorporate bus waveguides and relied on fibers to directly collect light from the disk. The first GaAs-AlGaAs microring resonator laterally coupled to bus waveguides was demonstrated by Rafizadeh et al. in 1997 at Northwestern University, Evanston, IL [51, 52]. Their smallest ring had a circumference of 32.8 $\mu m$. Since then, members of Ping-Tong Ho's group at the Laboratory for Physical Sciences (LPS), College Park, MD, have demonstrated both laterally and vertically coupled rings in GaAs-AlGaAs acting as multi ring devices, switches, routers, and mux/demux operation [53–61]. The GaInAsP-InP material system has proven problematic for passive microrings because of processing difficulties resulting in high device losses. Nevertheless, the first vertically coupled passive InP-based rings were demonstrated by Ho's group [59, 62, 63]. Other groups have concentrated on disk resonators; the group at the University of Southern California, for example, has demonstrated active and passive vertically coupled microdisk resonators [64, 65].

## 1.3 Putting the "Micro" in "Microring"

Initial efforts toward the fabrication of integrated ring resonators produced very large devices because the index contrast $\Delta n$ between the core and cladding was small, and operation with large radii of curvature minimizes bending losses [2, 66–69]. For example, the device fabricated by Honda et al. had $0.052 < \Delta n < 0.067$ and a radius of 4.5 cm [11]. Also, the device was multi mode, and there was considerable mode mixing, leading to a large background of non resonant light and the convolution of resonances from multiple modes.

The construction of microrings 10-$\mu m$ in diameter or smaller is a challenging effort often requiring high index contrast, anisotropically etched pedestal waveguide designs with ultrasmooth sidewalls. In addition, precise coupling gap widths with extremely tight tolerances are demanded