Chapter 1

Introduction

1.1 Microcavities

Optical microcavities are small devices that confine light for long periods of time by repeated reflection. They can take different geometric shapes−linear cavities such as vertical-cavity surface-emitting lasers (VCSEL) [1] and distributed-feedback lasers (DFB) [2], or circular cavities like micro droplets [3] and silicon micro-ring filters [4]. Microcavities have made a significant impact in both practical systems and laboratory research due to their small optical mode volume (V) and high quality factor (Q), which is a measure of the photon lifetime in the cavity. Fused silica (SiO_2) is the dielectric material of choice for solid microcavities thanks to its extremely low transmission losses in the optical communication band (1.55 μm). Braginsky and Ilchenko pioneered the study of ultra-high Q microspheres and predicted numerous nonlinear applications [5]. Subsequently, Gorodesky [6] and Vernooy [7] demonstrated silica microspheres with Q as high as 8×10^9, close to the intrinsic loss limits of silica in the visible band. Although higher quality factors are expected at longer wavelengths in the near-infrared (NIR) due to silica's absorption spectrum, in fact the Q did not increase. Both authors considered that the cause may be absorption loss due to water on the surface of or even inside the microsphere.

One requirement for ultra-high quality factor is low scattering caused by surface roughness. Indeed, a microsphere's nearly atomically smooth glass surface (1.7 nm rms roughness [7]) is made possible by surface-tension-controlled melting using a flame [7] or CO_2 laser [8]. The CO_2 laser reflow process, developed by Vahala for microspheres and later applied to microtoroids, can raise the Q factor from 1 million (microdisk) to over 100 million (microtoroid) by reducing surface roughness created during fabrication. Still, it is possible to produce high Q in a non-reflowed silica microdisk by carefully controlling the cavity mode profile. Kippenberg demonstrated a silica microdisk with Q as high as 60 million, by confining the optical mode away from the disk perimeter (where etch roughness is greatest) with a wedge feature [9].

The silica microtoroid is a planar on-chip resonator that was invented at Caltech and first reported by Armani [10]. Toroidal microcavities can confine light in ultra-small mode volumes (V =100 μm^3) [11] for photon lifetimes as long as 300 ns [12], and are easily fabricated on a silicon substrate [10].

Long photon lifetime and nearly ideal fiber taper coupling [13] of microtoroids enables researchers to experimentally observe nonlinear effects such as Raman scattering [12], parametric oscillation [14], third-harmonic generation [15], and radiation-pressure-driven mechanical oscillations [16]. The high Q/V figure for microtoroids, significantly better than that of microspheres, is important for cavity quantum electrodynamics (cQED) research. Aoki achieved strong coupling for the first time between the electromagnetic field of a microtoroid cavity and a cesium atom [17], made possible by more than 100,000 average round trips made by each photon. Photons are confined in the microtoroid cavity by repeated total-internal reflection, thus forming the whispering-gallery mode (WGM) structure of toroids. In every microcavity, a portion of the WGM's power resides outside of the cavity, this is the evanescent field component. The evanescent field in microtoroids allows fiber taper coupling of pump light, and makes the microtoroid extremely sensitive to both its own defects and the environment. High sensitivity to water vapor and dust limits the open-air quality factor of toroids over long periods of time. But, many benefits of the long interaction length and large interaction cross-section can be found. Armani demonstrated low-concentration biological sensing of interleukin-2 molecules with a silica microtoroid[18].

Microtoroids are naturally an ideal platform for making low-threshold single-frequency lasers. High quality factors permit laser action at very low concentrations (0.01% atm.), and small toroid diameters reduce the number of laser modes by virtue of the large free-spectral range (FSR) [19]. Yang adapted the solgel technique for making silica thin-films to fabricate single-frequency erbium-doped glass microtoroids [20], and Min studied ion-implanted erbium-doped microcavities [21].

1.2 Thesis outline

This thesis presents the author's scientific research into the physics defined by the interaction of high Q silica microcavities and materials including silver thin films, ytterbium ions, cesium ions, and water. The goal is to understand how these unique systems function, and explore applications that include optical communication, sensing, and cavity quantum electrodynamics. Low loss optical fiber tapers provide coupling of optical radiation to and from the resonator. As the basis for much of this work, microtoroid fabrication and experimental testing are first discussed in **Chapter 2**.

The previous work in erbium-doped silica microtoroid lasers by Yang paved the way for the investigation of ytterbium-doped lasers [20]. The first Yb:SiO_2 toroidal microcavity laser is demonstrated with a record-low pump threshold of 2 μW and single-frequency operation [19]. The laser performance is completely characterized in **Chapter 3**. In addition to several unique laser properties, ytterbium was chosen as the gain medium for its laser emission at 1 μm, where the absorption coefficient of water is 75 times less than at 1.5 μm [22]. **Chapter 4** explores the author's demonstration of the first-ever microcavity laser in water [23]. Simulation of the microtoroid laser in water is performed to find the optimum combination of doping concentration and toroid major diameter. This laser produces more than 2 μW of stable output power while completely submerged in water, opening up the possibility of an active laser sensor due to its narrow linewidth compared to passive cavities.

Chapter 5 focuses on the author's research on the interaction between high Q glass microresonators and metal thin films. Surface plasmon polaritons (SPPs) are electron density waves excited at the interface between metals and dielectric materials. Plasmonic waveguides and resonators are being intensely studied for possible applications in short-range communications, sensing, and filtering given their high field intensity and small mode volume [24, 25, 26, 27, 28]. The author, in collaboration with Bumki Min, demonstrates a high Q WGM microcavity constructed of a silica microdisk coated with a thin layer of silver [29]. The geometrical shape formed by specific fabrication techniques produced a SPP resonator with a record Q factor of 1,376, more than an order of magnitude higher than the previous micro-ring measurement [27]. The results of experimental measurement and finite-element modeling describe the operation of this plasmonic microcavity.

The issue of absorption loss due to water in silica microspheres was already mentioned. The author has directed research into the effects of water on microtoroids, with the purpose of increasing the current ultra-high quality factors ($Q < 5 \times 10^8$). **Chapter 6** presents the author's research into the affect of water on microtoroids. A novel vacuum chamber has been designed, built, and tested for laser reflow and fiber taper testing of microtoroids in vacuum. The aim of vacuum reflow is to eliminate any water that may limit Q. Laser reflow of microtoroids in vacuum has been demonstrated, and microtoroids with $Q = 2.2 \times 10^8$ have been fabricated. Continued research aims to increase quality factor as high as 1×10^{10}, due to the clean and dry vacuum environment.

The benefit of a wedge structure at the outer edge of the microdisk was previously highlighted. By confining the optical mode away from roughness caused by etching, the quality factor of microcavities can be increased by an order of magnitude. Putting this new technology to work, the author directed research into wedged whispering-gallery spiral waveguides for optical delay as described in **Chapter 7**. The WGM waveguides are only several microns in diameter, which allows them to be tightly packed into a spiral geometry. The spiral waveguide can provide over 1 m of optical delay packed into a 1 cm^2 surface area, a time delay sufficiently long enough to have applications in optical communications and laser-radar. Beam propagation simulations are performed for optimization of the center region of the spiral, where the WGM power flow changes direction from clockwise to counterclockwise. Spiral waveguides were designed, fabricated, and tested using a dual-taper coupler.

Also, the author developed the concept and performed simulations of a new short pulse microcavity laser. The pulsed laser consists of a Cr,Yb-doped silica microtoroid fabricated by the solgel method. Laser simulations included in **Chapter 7** predict the passive Q switched laser pulses to have 100 pJ energy and 1 ns duration.

In addition, the author contributed to the cavity quantum electrodynamics research of Professor Kimble at Caltech. Small mode volume and high-Q microtoroids were fabricated for experiments studying the interaction between the microtoroid's electromagnetic field and cesium atoms. Dayan demonstrated the first microcavity-atom photon turnstile in an experiment with a microtoroid [30]. Also, Aoki improved the efficiency of the single photon router to 60% by overcoupling the microtoroid and fiber taper [31].