Photonic whispering-gallery resonators in new environments

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Abstract

Optical whispering-gallery devices, like the microtoroid or microdisk, confine light at resonant frequencies and in ultra-small volumes for long periods of time. Such ultra-low loss resonators have been applied in diverse areas of scientific research, including low-threshold lasers on-chip, biological sensing, and quantum computing. In this thesis, novel ultra-low loss microstructures are studied for their unique characteristics and utility. The author investigates the interaction between microcavities and various environments in order to quantify the results and lay the foundation for future applications.

The first optical cavity studied is the microtoroid, which possesses ultra-high quality factor (Q) on account of its nearly atomic smooth surface, produced by surface-tension induced laser reflow. Ytterbium-doped silica microtoroids are fabricated by a sol-gel technique. The ytterbium microtoroid laser achieves record-low laser threshold (2 μW) in air, and produces the first laser output for a solid-state laser in water. This laser in water can be developed as an ultra-sensitive biological sensor, with potentially record sensitivity enabled by gain-narrowed linewidth. Also, a novel CO_2 laser reflow and microtoroid testing vacuum system is demonstrated. Fabrication and testing of microtoroids is performed in a vacuum chamber to study the effect of atmospheric water and upper limit of Q in microtoroids.

The selective reflow of microtoroids presents difficulties for integration of on-chip optical waveguides. As an alternative, dimension-preserving low-loss optical structures are researched for their unique applications. A gold-coated silica microdisk is fabricated, and demonstrates record and nearly-ideal quality factor (1,376) as a surface-plasmon polariton resonator. The hybrid optical-plasmonic mode structure is studied in simulation and experiment. The plasmonic resonator has ultra-low mode volume and high field confinement, making it suitable for short-range optical communication or sensing. Finally, a novel whispering-gallery optical delay line in a spiral geometry is designed and experimentally demonstrated. The center transition region of the spiral is optimized for low transmission loss by beam propagation simulation. A 1.4 m long spiral waveguide within a 1 cm^2 area is presented. The spiral waveguide structure is being developed as a real-time optical delay line with fiber-like loss, important for optical communication and signal processing.

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Yb-doped glass microcavity laser operation in water E. Ostby and K. Vahala, Optics Letters, **34**, 1153−1155 (2009).

High-Q surface-plasmon-polariton whispering-gallery microcavity B. Min, E. Ostby, V. Sorger, E. Ulin-Avila, L. Yang, X. Zhang, and K. Vahala, Nature, **457**, 455−458 (2009).

Ultralow-threshold Yb3+:SiO2 glass laser fabricated by the solgel process E. Ostby, L. Yang, and K. Vahala, Optics Letters, **32**, 2650−2652 (2007).

A Photon Turnstile Dynamically Regulated by One Atom B. Dayan, A. Parkins, T.Aoki, E. Ostby, K. Vahala, and H. Kimble, Science, **319**, 1062−1065 (2008).

Efficient routing of single photons by one atom and a microtoroidal cavity T. Aoki, A. Parkins D. Alton, C. Regal, B. Dayan, E. Ostby, K. Vahala, and H. Kimble, Physical Review Letters, **102**, 083601 (2009).

Wavelength-independent coupler from fiber to an on-chip cavity, demonstrated over an 850nm span T. Carmon, S. Wang, E. Ostby, and K. Vahala, Optics Express, **15**, 7677−7681 (2007).