Ultra-high Q whispering-gallery microcavities for narrow-linewidth lasers and optoelectronic oscillators

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High-Q (10^8 - 10^{10}) microcavities with whispering-gallery modes are enabling component for lasers and photonics. Besides optical locking of diode lasers, we demonstrate a fiber-coupled erbium-doped microsphere laser and a microsphere-based optoelectronic microwave oscillator. We discuss integration aspects in context of recent novel coupling methods, and present a novel-geometry microcavity with increased free spectral range (~3nm at 1550nm) and finesse $>10^4$.

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In the growing field of microcavity science and applications, microspheres with whispering-gallery (WG) modes [1] stand out as exceptional type of cavities, with the dimensions compatible with microfabricated devices and the quality-factor 10^8-10^{10} normally obtained in large Fabry-Perot "supercavities". Apart from passive component applications, the above combination allows creation of very small high-spectral purity sources in optical and microwave bands. **1)**Potential **integration** of microspheres in compact functional devices stimulated the search for efficient **coupling methods to fibers and waveguides,** to replace bulky prism couplers used in early experiments. Together with recent integrated waveguide coupling demonstration, previously reported fiber-coupling options relied on tailoring of regular waveguide effective index n_{fiber} to match that of the azimuthal propagation of WG modes n_{sphere} [2]. We have demonstrated a simple coupling method for standard optical fibers: the tip of the fiber is angle cut to provide total internal reflection (TIR) of the core mode, and the evanescent wave of TIR is synchronized with WG modes, by choosing the angle $\Phi = arcsin(n_{sphere}/n_{fiber})$ [3]. Analog of this coupler will be important in integrated optics: direct phase matching with glass spheres is not possible for high-index substrates. **2)Frequency locking of semiconductor lasers** by optical feedback from microsphere has been demonstrated to reduce emission linewidth into the kHz domain [4]. In the tabletop experiment, two lasers at 852nm were locked to adjacent WG modes of a microsphere with loaded Q-factor $\sim 2\times10^7$. The ~600MHz beatnote revealed technical linewidth of about 20kHz (limited by phase noises in the feedback), compared to ~20MHz free-running, and the natural linewidth <1kHz derived from the Lorentzian fit outside 100kHz from the carrier. Integrated option of the system will eliminate technical noises from free-space optics and will be a chip-size source with spectral purity currently available in expensive larger systems. **3)Direct laser oscillation in microspheres** has been previously studied with the aim of achieving ultra-low threshold operation. Thresholds at the level of ~100nW per lasing mode have been achieved in $Nd:SiO_2$ microspheres. Later, laser oscillation in neodymium and erbium doped ZBLAN spheres was obtained. In all cases [5], pumping and laser output was provided via the adjacent prism. We have demonstrated a fiber coupled microsphere laser at 1550nm; with the cavity fabricated of erbium-doped alumosilicate glass, and pumping and laser output provided by a single angle-polished fiber coupler. Single mode operation and maximum power of 4μW in the output fiber were obtained, with the estimated absorbed pump power of 220μW at 977nm. **4)Microspheres** can be used **to produce spectrally pure microwave** signals. In "conventional" optoelectronic oscillator (OEO), oscillation begins in a feedback loop formed by a electro-optic modulator, fiber delay, high-speed photodetector and microwave filter and amplifier. Phase noise is suppressed with the increasing storage time of the delay, achieving –140dBc/Hz at 10kHz form 10GHz carrier, with 2km-long fiber [6]. Unique OEO advantage is immediate photonic output. All OEO components, except fiber delay, can be potentially combined on a single chip. Microsphere, with their few-microsecond range photon storage times (equivalent to ~1km propagation), can replace bulky fiber spools and open the route to a truly compact hybrid OEO. Since the mode spacing in microspheres ("small" free spectral range, FSR) falls into the microwave band, the microsphere-based OEO does not require microwave filter and can oscillate at a frequency offset between two modes. In preliminary experiments, we have obtained microwave oscillation at 6-10GHz in the microsphere-based OEO, in two configurations: a)with external DFB pump laser and b)with the ring laser including the microsphere and optical amplifier. **5)**Despite their small dimensions, because of high symmetry **microspheres exhibit** relatively **dense spectrum** of WG modes. "Large" FSR – defined by the roundtrip of light along the "equator"– is 200-700GHz in a silica sphere of diameter between 400…150 micron (1.3…5.4nm near the center wavelength 1550nm). Although degenerate in ideal spheres, modes with different "latitudinal" structure are split in slightly eccentric cavity (typical eccentricity ~1% with current fabrication technique). As a result, even with the optimized evanescent coupler, typical observed WG mode spacing is between 1 and 10GHz. Although favorable for OEO, such a dense spectrum complicates laser locking solutions, filtering etc. "Single-mode" spectrum of WG modes is readily obtained in planar waveguide rings [7], but their Q-factor normally does not exceed 10^4-10^5 because of much higher scattering losses. In our experiment we approached "single mode" operation by fabricating a **highly oblate spheroidal cavity**. The measured spectrum exhibited only **two modes within large FSR of –380GHz** (germanosilicate glass n =1.48, ellipsoid semiaxes 82μm and 40μm, wavelength 1550nm). With the quality-factor of $\sim 1\times10^7$, the finesse of the cavity exceeded 10^4.

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