# Photonic Frequency Synthesis and Control with Whispering Gallery Mode Resonators

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*Abstract:* Optical whispering-gallery-mode (WGM) resonators exhibit bandwidth in the hundred kilohertz to gigahertz range. In microwave photonics applications, this bandwidth corresponds to the wide range of equivalent radio-frequency Q-factors (between 10 and $10^6$ for the X-band). This unique flexibility, in combination with proper choice of highly transparent and/or nonlinear resonator material, allows for realization of a number of high performance microwave photonic devices: tunable and multi-pole filters, resonant electro-optic modulator, photonic microwave receiver, and opto-electronic microwave oscillator.

*Introduction:* Generation and processing of RF signals by optical methods utilizes the benefit and convenience of bandwidth management provided by the growing array of free-space, fiber-optic and integrated-optic devices. Until recently, elements equivalent to relatively low-Q RF photonic analogs such as crude bandpass filters were demonstrated. In this paper we describe photonic applications of ultra-high-Q optical resonators with whispering gallery modes (WGMs), allowing the realization of high performance devices. Combinations of very high optical Q-factor ($Q = 10^6 \div 10^{10}$, depending on the material), small size, and potential for integration with planar waveguide and fiber optics make these resonators attractive as new components for photonic systems. Because of very

small optical bandwidth (down to $100\,kHz$ and below), these resonators present an unparalleled capability to surpass the performance of high-Q microwave devices (such as narrow-band filters and oscillators based on metal cavities or cryogenic dielectric resonators). Since optical bandwidth is constant, equivalent quality-factor in photonic applications grows with RF frequency – oppositely to RF devices – and becomes especially attractive at microwave and millimeter-wave ranges.

WGMs are in essence closed circulating waves undergoing total internal reflection inside the axi-symmetric body of a transparent dielectric. Because of high refractive index contrast, radiative losses are negligible when the radius of the resonator exceeds several tens of wavelengths, and the Q is limited by material losses that are extremely small in optical materials. For example, the equivalent loss tangent in fused silica is $\approx 7\times10^{-12}$ near the wavelength of $1.55\,\mu m$ which allows $Q\approx10^{11}$ [1].

*WGM filters:* Ultra-high-Q WG modes were first observed in solidified droplets of amorphous materials (such as fused silica) – microspheres. Several effective approaches for coupling light into and out of such resonators have been devised. The observed spectrum of WGMs consists of families of modes separated in frequency by intervals of a few GHz. Preparation of resonators with predetermined resonance frequencies is very difficult with the melt technique. Tuning of WGMs across the free spectral range (FSR) can be achieved by

temperature change, however for some applications trimming the resonators to achieve exact positions of resonance is required.

We have recently demonstrated frequency trimming of WGMs using UV light photosensitivity in microresonators made out of germania doped fused silica [2]. The method is based on the photosensitivity of the material. When exposed to UV light, this material undergoes a small permanent change in structure that alters its index of refraction that results in a uniform translation of the resonant frequencies of a WGM microresonator. We have experimentally realized $18\ GHz$ permanent frequency shifts obtained with high-Q ($Q = 10^8$) WGMs at $1.55\ \mu m$. This is enough to tune a resonance over a full FSR of the WGM resonator.

The ability to permanently adjust the WGM spectrum allowed us to demonstrate a two-pole optical filter with bandwidth $30\ MHz$ using two coupled microresonators (see in Fig.1) exactly tuned to each other in frequency at a given wavelength [3]. The filter has flat-top characteristic and a steeper roll-off than in a single microresonator that has a Lorentzian transfer function.

Amorphous materials, including fused silica that allows achieving ultra-high-Q's, can only be used with the melt technique for preparing resonators. To access a broader range of materials, including those with high nonlinearities, we have adapted polishing techniques to fabricate crystalline WG resonators with very high Q-factors. We recently demonstrated a narrow-band electro-optically

tunable frequency filter based on a whispering gallery mode $LiNbO_3$ cavity (see in Fig.2) with a $10\ GHz$ free spectral range [4]. The filter operates at $1.55\ \mu m$ with a $30\ MHz$ bandwidth and can be electro-optically tuned at $10\ GHz$ in linear regime with approximately $40\ MHz/V$ tuning rate. The filter had $12\ dB$ fiber-to-fiber insertion loss, though we have achieved $4.5\ dB$ insertion loss quite recently. To demonstrate the device performance, we configured it as a photonic microwave filter for transmission of a video signal at a microwave band. Such a photonic architecture allows for construction of a uniform platform for RF through millimeter-wave systems that would otherwise require different sets of bulky and expensive hardware if implemented directly at RF frequencies.

*WGM modulator and photonic receiver:* By changing the structure of the tunable filter we have implemented an electro-optic modulator based on WGM $LiNbO_3$ resonators (see in Fig.3). We observed an efficient modulation of light with a microwave field at $9\ GHz$ with applied microwave power of about $10\ mW$ [5], and at $3.4\ GHz$ with applied microwave power of about $1\ mW$. The modulator is fully integrated with input optics and has a fiber-to-fiber insertion loss of $5.5\ dB$. Their optical quality factor depends on the chosen mode and varies from $Q = 10^6$ to $Q = 3\times10^7$ at $780\ nm$ and $Q = 2\times10^8$ at $1.55\ \mu m$. The quality factor of the microwave resonator is approximately equal to $Q_M = 100$. Used as a receiver, the modulator allows us to detect microwave radiation at the nanoWatt level[6]. The

performance of the modulators/receivers remains stable during weeks of operation, and the quality factors of WGMs do not degrade with time.

*WGM opto-electronic oscillator:* One of potential applications of the WGM modulators is a compact and efficient opto-electronic oscillator (OEO). The opto-electronic oscillator is a device that produces spectrally pure signals at many tens of gigahertz based on photonic techniques, and thus overcomes some of the inherent limitations of the conventional electronic devices. The OEO is a generic architecture consisting of a laser as the source of light energy [7]. The laser radiation propagates through a modulator and an optical energy storage element, before it is converted to the electrical energy with a photodetector. The electrical signal at the output of the modulator is amplified and filtered before it is feed back to the modulator, thereby completing a feedback loop with gain, which generates sustained oscillation at a frequency determined by the filter.

A scheme for the WGM OEO is shown in Fig.4. Light from a laser is sent to the modulator, a WGM ultrahigh-Q delay element, and the photodiode. No fiber delay lines are necessary because of the narrowband WGM delay. The high-Q microwave filter is not needed as well. We have performed preliminary experimental studies of an OEO based on this high-Q WGM electro-optic modulator and obtained microwave oscillations in the system. Future work will concentrate on improving the performance of the oscillator to the level achieved with the highest performance microwave oscillators.

In conclusion, we have discussed novel, photonic devices based on whispering gallery mode resonators. Despite their high performance, these devices are preliminary examples of new signal processing functions that can be based on optical WGM micro-resonators. We believe future devices based on this technology will find various applications for processing and control of microwave signals at frequencies up to $300\ GHz$.

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**Figures:**

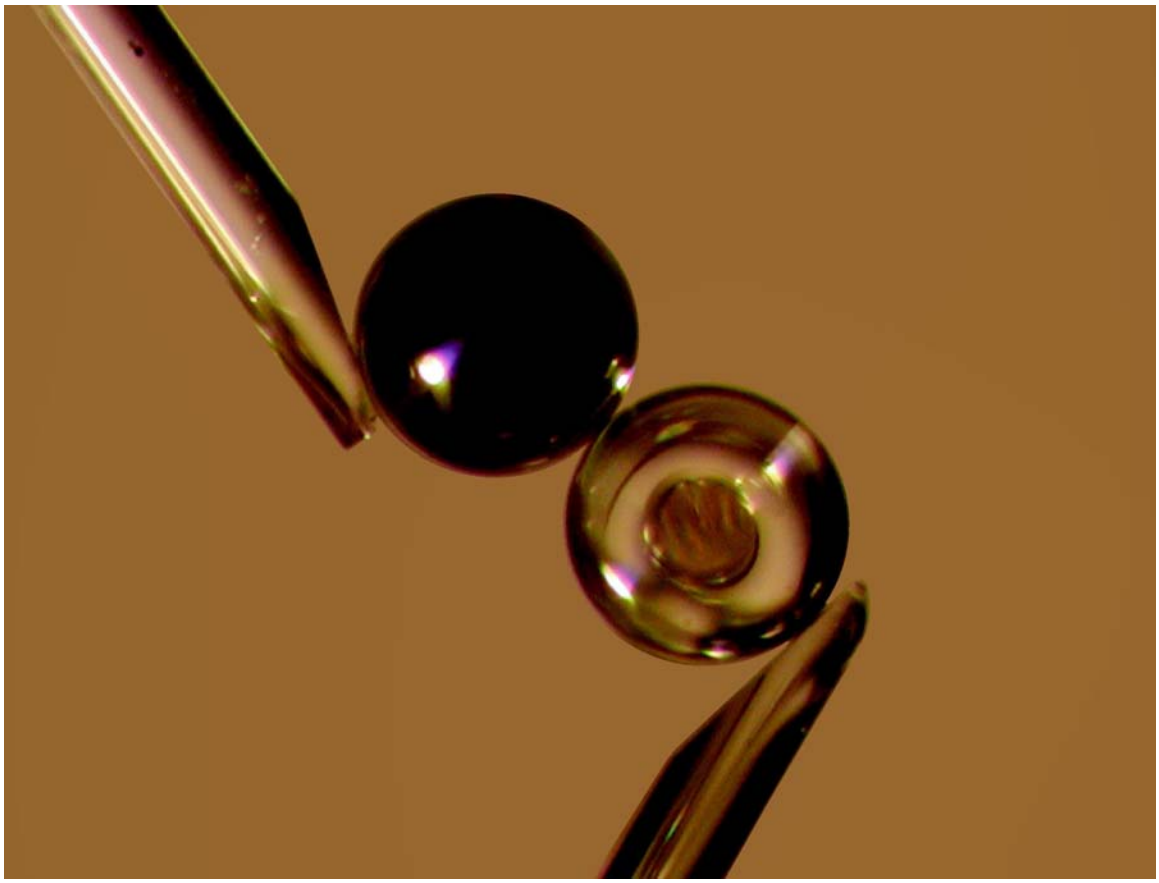

Figure 1. Coupled whispering gallery mode resonators are equivalent to a second order optical filter.

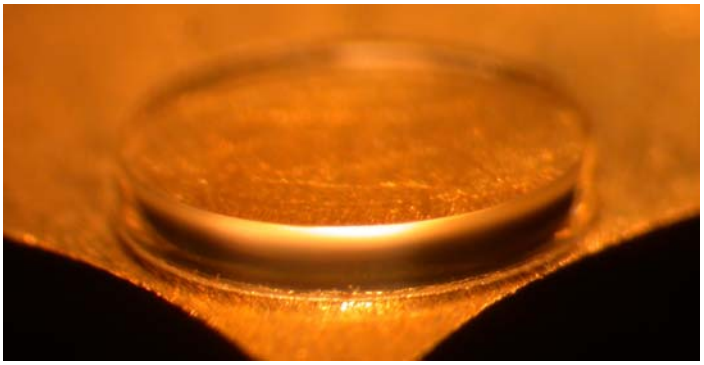

Figure 2. Whispering gallery mode resonator made of lithium-niobate crystal.

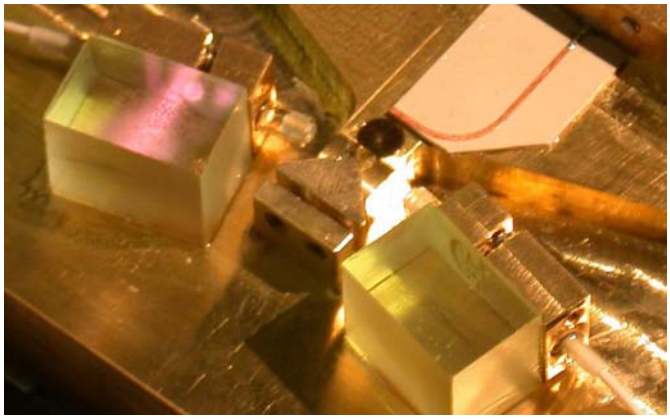

Figure 3. Electro-optical modulator based on a lithium-niobate WGM resonator.

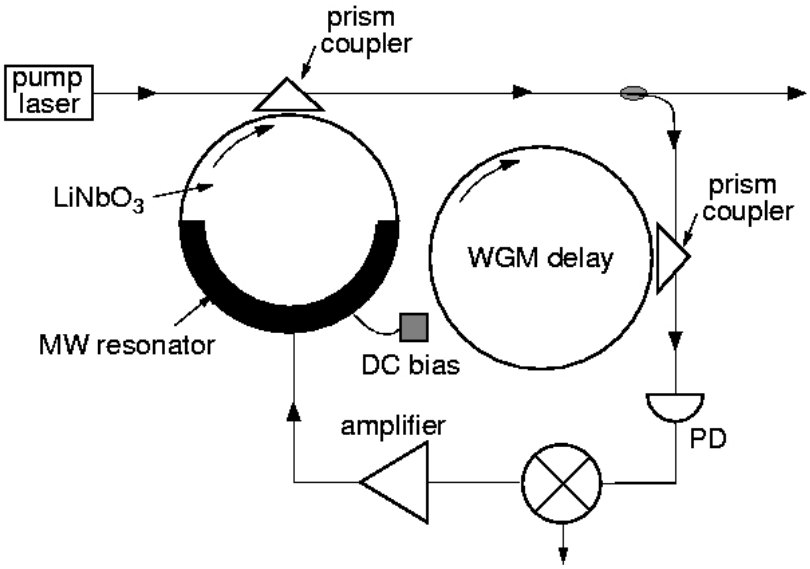


Figure 4. Schematic diagram of the WGM resonator based OEO

*Key Words:* Optical filters, Multiplexing Equipment, Optical communications, Optical fibre networks