Linear and nonlinear behavior of crystalline optical whispering gallery mode resonators

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Abstract: We demonstrate strong nonlinear behavior of high-Q whispering gallery mode (WGM) resonators made out of various crystals and devices based on the resonators. The maximum WGM optical Q-fact or achieved at room temperature exceeds 2×10^{10}.

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Confinement of photons in small spatial volumes for long periods of time has been of interest for both fundamental studies and practical applications. That is why WGM resonators become more and more important in modern optics.[1–4] Among many parameters, such as efficiency of in- and out-coupling, mode volume, free spectral range etc., that characterize the resonator, quality (Q) factor is the basic one. The Q-factor is related to the lifetime of light in the resonator mode (τ) as $Q = 2\pi\nu\tau$, where ν is the linear frequency of the mode. The ring down time corresponding to a mode with $Q = 2 \times 10^{10}$ and wavelength $\lambda = 1.3$ μm is 15 μs, thus making ultra-high Q resonators potentially attractive as light storage devices, if such high Q's could be obtained. Such a long photon lifetime could increase nonlinear optical interactions significantly.

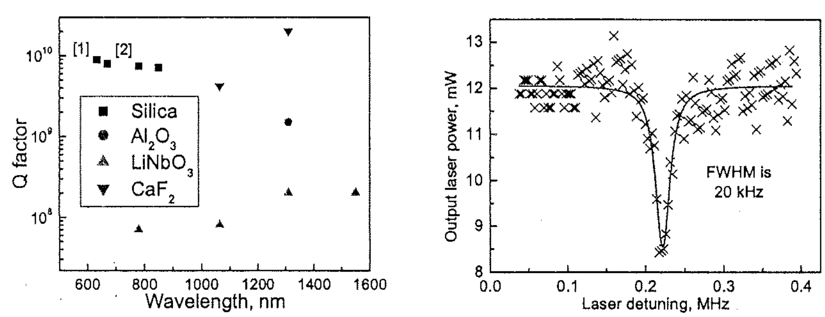

Figure 1. Left: The maximum Q-factors achieved with crystalline resonators vs the best Q-factors measures in the fused silica microspheres: [1] Gorodetsky *et al.*, Opt. Lett. **21**, 453 (1996); [2] Vernooy *et al.*, Opt. Lett. **23**, 247 (1998); Right: Typical response function of the calcium fluoride WGM resonator.

We have studied WGM resonators fabricated of calcium fluoride and few other crystals and measured their quality factors. The highest achieved Q values are presented in Fig. 1. Such a high optical Q-factor resulted in observation of several nonlinear optical effects. Two of them are instability due to strong thermal nonlinearity Fig. 2 (Left) and optical oscillations based on four wave mixing Fig. 2 (Right).

Another nonlinear optical effect we demonstrated is parametric frequency upconversion with periodically poled lithium niobate (PPLN) disc Fig. 3. Due to high Q-factor ($Q > 10^7$ for unloaded, and $Q > 5 \times 10^6$

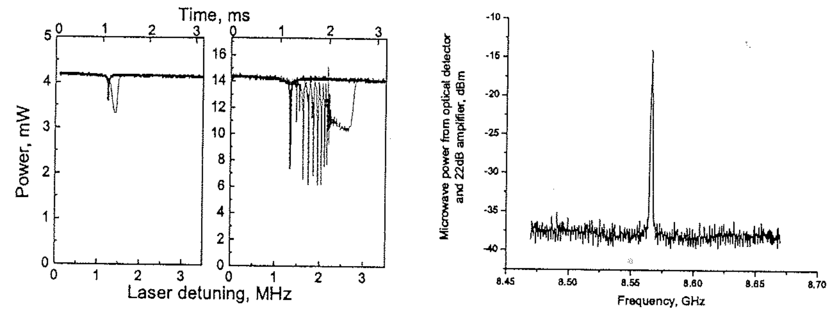

Figure 2. Left: Interlaced resonant curves as scanned in two different laser frequency sweep directions. The hysteretic feature occurs due to thermal oscillatory instability of the slope of nonlinear resonant curve. Heating of the resonator shifts the mode to higher frequency. The laser drags the mode if the laser frequency increases slowly with time. On the other hand, the laser jumps through the mode if the laser frequency decreases with time. The effect increases with the increase of optical power in the mode (c.f. left and right hand side traces). Quality factor of the mode exceeds 6×10^9. Right: Microwave power on the optical detector's outlet. The inlet of the detector is receiving optical beam from the CaF_2 cavity. Due to four wave mixing two identical drive photons transform to two photons frequency of which is shifted up and down by FSR of the resonator. Beating of this frequency up- and down-shifted light beams with the drive results in the microwave signal we observed.

for loaded resonator), we realized frequency doubling at 1550 nm with almost 50% efficiency at 25 mW pump power. The efficiency was restricted due to not optimal structure of the periodical poling of the resonator material, temperature and photorefractive effects. The method allows to obtain much higher efficiency with proper poling. The follow-up studies of the parametric processes in WGM PPLN resonators are also important because it has been predicted that an optical parametric oscillator (OPO) based on a WGM PPLN resonator might have power threshold below a microWatt[6] – orders of magnitude less than that of the state-of-the-art OPOs, typically at 0.5 mW level.[7]

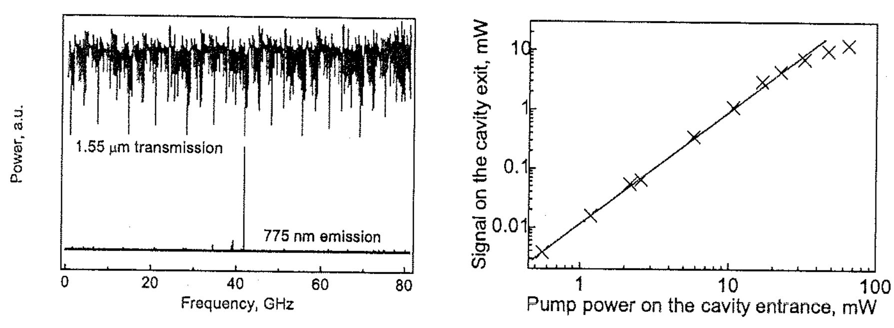

Figure 3. Left: Top plot is a spectra of the cavity at 1550 nm. Bottom plot is the 775 nm output due to 1550 nm doubling in the PPLN resonator. Right: Efficiency of the frequency conversion vs 1550 nm light power.

LiNbO3 resonators also result in electro-optical effects useful for photonics applications. We have realized a miniature resonant electro-optically tunable third-order Butterworth filter.[5] The filter is based on three WGM disc cavities fabricated from a commercially available lithium niobate wafer. The filter, operating at the 1550 nm wavelength, has approximately 30 MHz linewidth and can be tuned in the range of ±12 GHz by applying DC voltage of ±150 V to an electrode. The free spectral range of each resonator is approximately 13.3 GHz, and the filter may be tuned practically at any optical frequency in the transparency range of lithium niobate. An example of filter spectra is shown at Fig. 4.

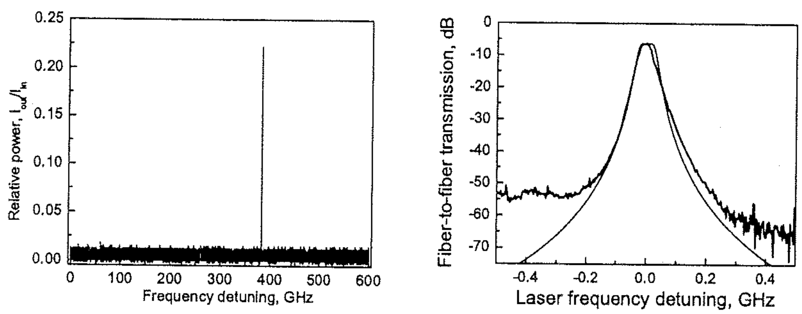

Figure 4. Left: Filter's spectrum, linear scale. Demonstrated width of the spectra is limited by the tunability of the laser. Filter's spectrum, Log scale. The filter function is fitted with third order Butterworth function.

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