

# Radiation-Pressure-Driven Micro-Mechanical Oscillator

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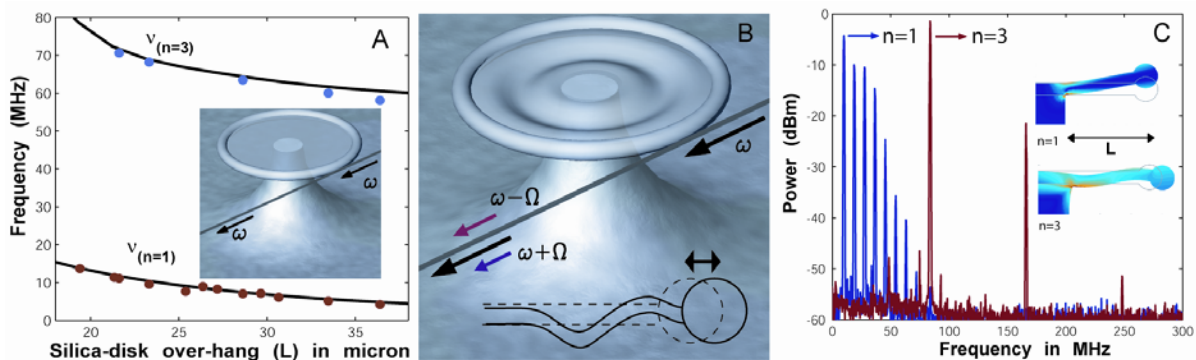
**Abstract:** We demonstrate for the first time, self generation of mechanical vibrations at RF frequencies stimulated directly by the radiation pressure of circulating photons within optical micro-cavities.

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In this work, we describe a radiation-pressure-induced effect emerging from the trend in photonics towards smaller size and lower loss (high Q factor) microresonators. In particular we demonstrate a novel class of radio frequency (RF) oscillators, based on the cooperative interaction of optical and mechanical resonators *co-located* within the same device. Embodied within a microscale, chip-based device this mechanism suggests new technologies that leverage the phenomenon within photonics.

Microtoroid structures<sup>1</sup> are made of silica and attached to a silicon cylindrical pillar (see fig. 1). When coupled to a waveguide, the high quality factor of micro-toroids ( $\sim 10^8$ ) results in optical power build-up that can exceed 100 Watts of circulating power for only 1 mWatt of waveguide input power. The resulting radiation pressure due to confinement of these high optical powers in micron-scale volumes excites the vibrational modes of the toroidal structures. Assuming first that the optical pump wave frequency ( $\omega$ ) is nearly resonant (but not exactly resonant) with the optical mode, radiation pressure, caused by circulating photons inside the cavity, will induce deformation of the toroidal structure and change the resonant frequency of the micro-cavity through dimensional changes in the modal round-trip optical path length. This resonant shift either lowers or raises the coupled optical pump power, depending upon the sign of the detuning of pump frequency relative to the microcavity resonant frequency. When the pump laser is detuned to the high-frequency tail of the optical mode, the phase relationship between optical pressure and microcavity deformation results in net power transfer from the optical pump to the mechanical mode. This transfer manifests itself mathematically as a mechanical gain, for the mechanical oscillations, with a corresponding threshold optical power. Interaction of the vibrating resonator (at mechanical eigen frequency  $\Omega$ ) with photons inside the cavity results in creation of photons down-shifted (stokes sideband,  $\omega - \Omega$ ) or up-shifted (anti-stokes sideband,  $\omega + \Omega$ ) in energy from the original photons by the RF frequency of the vibrations. Beating of the original pump wave with the up/down-shifted, optical sidebands therefore results in oscillations in optical power transmission at the mechanical frequencies of the structure. A rendering of this mechanism is provided in figure 1.



**Figure 1:** Panel A contains a plot of the mechanical oscillation frequency versus the cavity overhang  $L$  (see panel C inset for definition of  $L$ ) for the first- and third order flexural modes. Dots are experimentally measured frequencies and lines are the result of numerical calculations. Inset is an illustration of the toroidal structure coupled to a tapered optical fiber when the CW input power is below threshold. Panel B illustrates the above threshold case for the  $n=3$  mode. Inset of panel B shows the exaggerated cross-section of the third order mode and variation of the toroid

radius as a result of these oscillations. **Panel C** shows the measured, spectral content of pump-power transmission as observed on an electrical spectrum analyzer. The inset shows the numerically modeled cross-sectional plot (exaggerated for clarity) of the strain field for the first and third vibrational eigenmodes of a toroidal silica micro-cavity on a silicon post. The stress field is superimposed (color coded).

We observed these oscillations for pump coupling to sufficiently high quality factor optical modes ( $Q > 10^7$  or 10 ns photon lifetime at infra-red wavelengths). Spectral analysis of the detected, transmitted optical power using a high-resolution electrical spectrum analyzer, as shown in figure 1, revealed extremely narrow peaks (linewidths of less than 10 Hz limited by the equipment resolution) at a frequency typically in the range of 10-100 MHz as well as at harmonics of this fundamental frequency. As can be seen in figure 1C, two, distinct fundamental oscillation frequencies (and their harmonics) were observed: a low frequency mode ( $\sim 2$ -20 MHz) and a high frequency mode ( $\sim 40$ -100 MHz). The eigen-frequencies of the mechanical modes of the toroidal structures were investigated numerically to confirm their mechanical origin. Close agreement of the RF oscillation frequencies with the results of the numerical modeling (about 2% average error) confirms that the first ( $n=1$ ) and third ( $n=3$ ) order flexural modes are responsible for creating the observed low- and high- frequency families of oscillations, respectively. The mechanical origin of these oscillations was also confirmed by lowering a metallic micro-probe into proximity with the plane of resonator. Upon approach by the probe, the amplitude of the optical power oscillations was observed to at first diminish and ultimately fully quench on probe contact.

This system can be modelled<sup>2</sup> using a set of coupled differential equations: one governing the harmonic motion of the flexing toroid and a second governing the resonant optical field. The threshold for onset of mechanical oscillations can be found by solving these equations self-consistently:

$$P_{threshold} = K_{opt-mech} \frac{Q_c}{Q_{total}^4 Q_{mech}} f(d) \quad (1)$$

$P_{threshold}$  denotes the incident (in the waveguide) threshold power (i.e., not the power coupled into the resonator). Also,  $Q_{total}$  is the total quality factor of the optical mode, (made up of an intrinsic contribution  $Q_0$  and a waveguide-loading contribution  $Q_c$ ), and  $Q_{mech}$  is the intrinsic quality factor of the mechanical mode.  $d$  is the detuning factor, giving the normalized detuning of the optical frequency from the resonant frequency of the cavity ( $\omega_0$ ) in units of its linewidth (i.e.  $d = Q_{total}(\omega - \omega_0)/2\omega_0$ ) and  $f(d) = (1 + d^2)^3/d$  is a factor that is positive for blue-detuning of the pump (and negative for red detuning). This factor, emerging from the analysis, reflects the intuitive picture described above requiring a particular phase relation between radiation pressure and cavity deformation in order that power is transferred from the optical mode to the mechanical mode. The constant  $K_{opt-mech} = R^2 \omega_0^2 m_{eff} \Omega / 64$ , determines how strongly the optical and mechanical modes are coupled and depends upon the radius  $R$  of the micro-toroid, its vibrational frequency  $\Omega$  and the effective vibrating mass  $m_{eff}$ . Equation (1) shows that the threshold power scales approximately with  $1/Q_{total}^3$ , and emphasizes the importance of high optical  $Q$ .

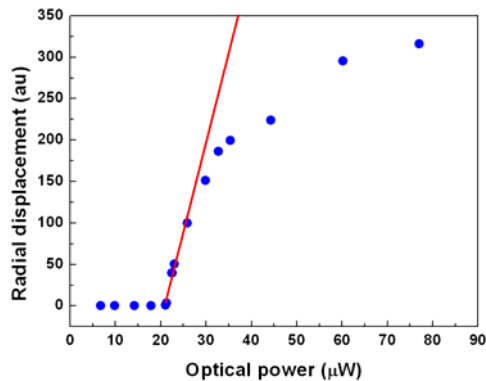
In order to investigate this effect an optical pump and probe approach was used with two laser beams (a strong pump and a weak probe) individually resonant with two whispering gallery mode optical resonances. The pump laser in the 1550 nm band and probe laser in the 1480 nm band were coupled to the micro-cavity using a tapered optical fiber formed by heating and stretching a length of single mode fiber. The Fourier component of the transmitted probe power at the mechanical resonant frequency ( $\Omega$ ) was monitored by the electrical spectrum analyzer. The intensity of this signal, proportional to the amplitude of the vibrations caused by the pump wave, was measured as a function of pump power. Figure 2 contains typical results of these measurements and shows a clear threshold for the vibrational oscillations. The data in figure 2 also seems to suggest that the amplitude of the vibrations saturates at high pump powers. Numerical modelling of this behaviour shows that this behaviour can be attributed to the induced frequency shifts of the cavity which, for higher pump power levels, exceed the cavity linewidth. This, in turn, reduces the efficacy of the pumping mechanism as the pump wave spends a progressively smaller fraction of time on resonance during each mechanical cycle.

As a test of the model in predicting measured threshold power, one of the samples studied in this work exhibited the following measured parameters:  $Q_{total} = 2 \times 10^6$ ,  $\Omega = 42.3$  MHz ( $n=3$ ) and threshold power of  $520 \mu W$  for  $d \approx 1$ . The resonator had a major radius of about  $23 \mu m$  and a mechanical  $Q$  factor of  $Q_m = 210$ . Using these parameters in equation (1) for threshold power and using the actual mass of the resonator for the effective mass ( $m_{eff} \approx m \approx 3 \times 10^{-11} Kg$ ) results in a theoretical threshold estimate of  $495 \mu W$ , which is in close agreement with the actual value.

Mechanical oscillations in micro-structures can be generated using alternative methods and it is therefore important to distinguish the current results from other methods of excitation. For example, ref. 3 describes thermally actuated mechanical vibrations of a silicon disk. However, for the structures studied in this work the thermal time

constant involved in conduction of the generated heat from the optical mode to the remainder of the structure<sup>4</sup> ( $\tau_{thermal}$ ) is in the order of  $5\mu s$  and is expected to be highly inefficient in modulating the structure at RF rates such as those observed here. Also significant is the expected threshold dependence on optical Q for thermally driven instabilities. Because resonator deformation for a thermally driven process (as opposed to radiation pressure) depends on coupled optical power (not circulating power) one expects an inverse quadratic scaling of the threshold power with optical Q ( $P_{threshold} \propto Q^{-2}$ ) for thermally induced as opposed to  $P_{threshold} \propto Q^{-3}$  for radiation pressure induced oscillations. This Q dependence has been verified, further confirming radiation pressure as the origin of the observed mechanical oscillations.

The above findings demonstrate a new class of hybrid oscillators where a continuous source of pump laser power generates radio frequency mechanical vibrations of a micro-scale structure (without utilizing any type of external feedback system). These oscillations imprint onto the optical pump, now an optical carrier of RF frequencies. Realization of this effect is by no means restricted to the toroidal micro-cavities as we were also able to observe similar oscillations in silica micro-spheres. Therefore it is likely that all optical cavities are susceptible to these oscillations at various optical powers. The inverse cubic dependence of threshold power suggests that current efforts directed towards realization of higher Q optical microcavities will only tend to accelerate the observation of these oscillations in other microcavity systems. Beyond applications in RF micro-mechanical oscillators on a chip<sup>5</sup>, the ramifications of the radiation pressure induced opto-mechanical coupling have been theoretically explored in a variety of fundamental studies. In the Laser Interferometer Gravitational Wave Observatory (LIGO) community, it is proposed during the past few years that the so-called parametric instability could potentially limit the maximum stored energy in Fabry-Perot cavities used in the LIGO project and hence also the sensitivity of the gravitational wave detector<sup>2,6</sup>. This effect, never observed in the macro-scale, is more likely to occur in optical micro-resonators, as the threshold power scales rapidly with dimensions:  $P_{th} \propto R^4$ . The work presented here is to the authors' knowledge the first demonstration of the radiation pressure induced parametric instability in optical resonators of any kind. In addition, high precision standard quantum limited measurements of position<sup>7</sup>, and the entanglement of light and macroscopic objects<sup>8</sup> are other exciting areas where this interaction can become useful.



**Figure 2.** Measured mechanical oscillator displacement as a function of the optical pump power showing threshold behaviour. Oscillations initiate at about  $20\mu W$  of input power and start to saturate for higher values of pump power. This saturation is associated with the lower optical-mechanical coupling at displacements large enough to shift the resonant frequency of the optical mode by greater than its linewidth.

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