

# Radiation-pressure-induced regenerative mechanical oscillations in optical microcavities

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*APS March meeting 2006*



# Microtoroid optical resonator

## ◆ Microtoroid resonator

### ◆ High $Q$ -factor

- Long photon lifetime ( $\tau_p$ )
- Large circulating power ( $P_{\text{circ}}$ )

### ◆ Small mode volume

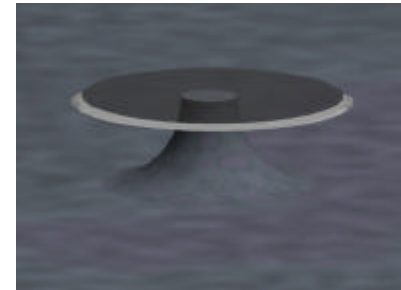
- Large intensity

### ◆ Monolithic fabrication

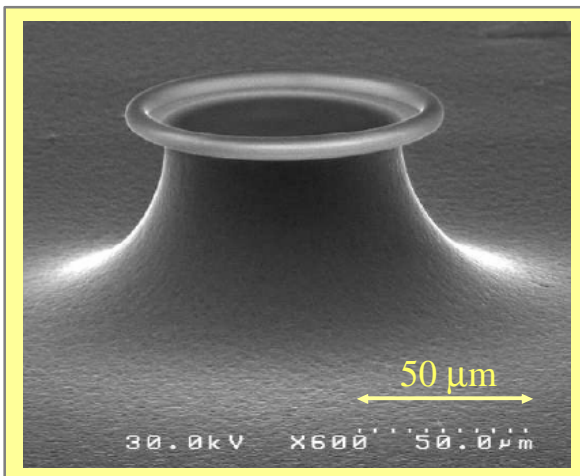
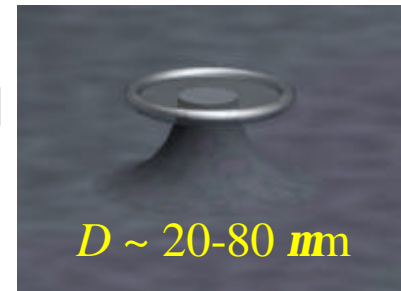
Circular  $\text{SiO}_2$  pad  
(HF wet etching)



Silicon pillar  
( $\text{XeF}_2$  dry etching)



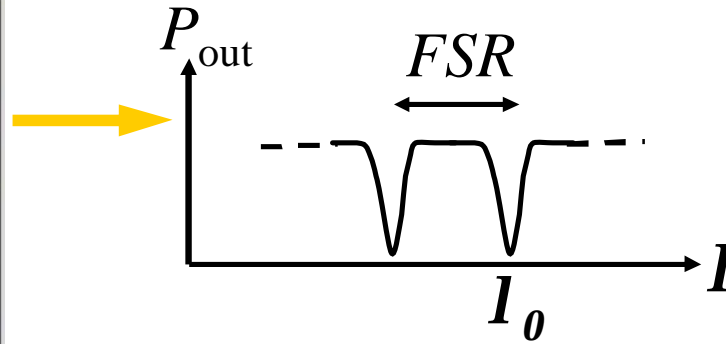
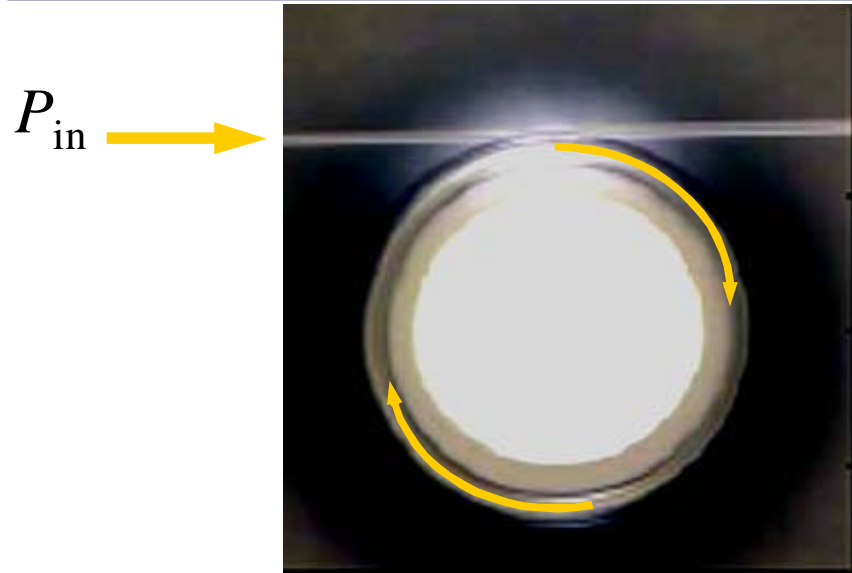
Silica microtoroid  
( $\text{CO}_2$  laser reflow)



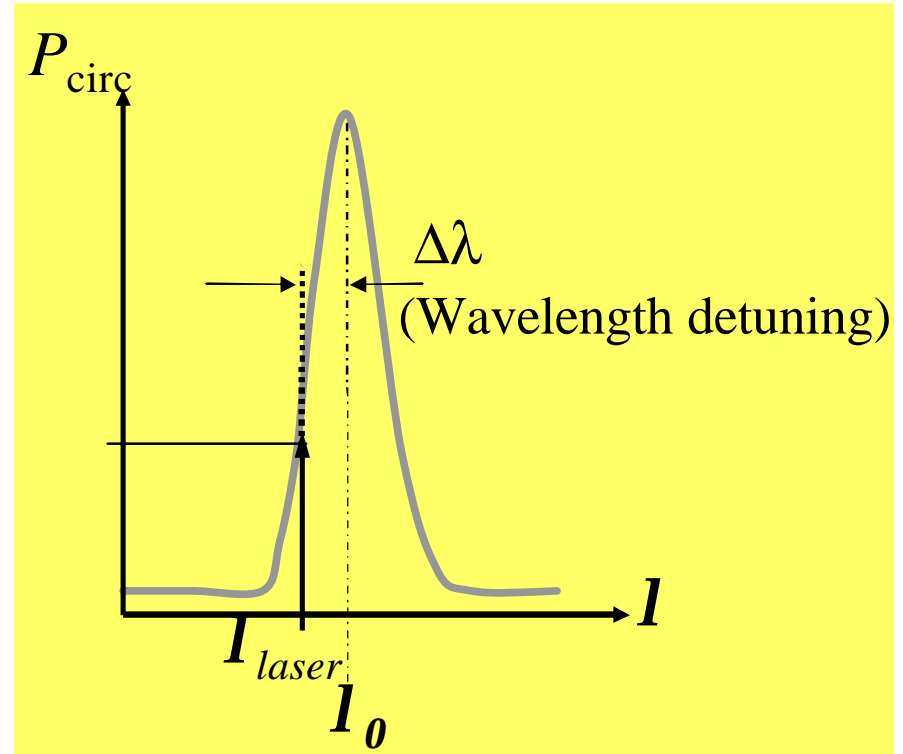
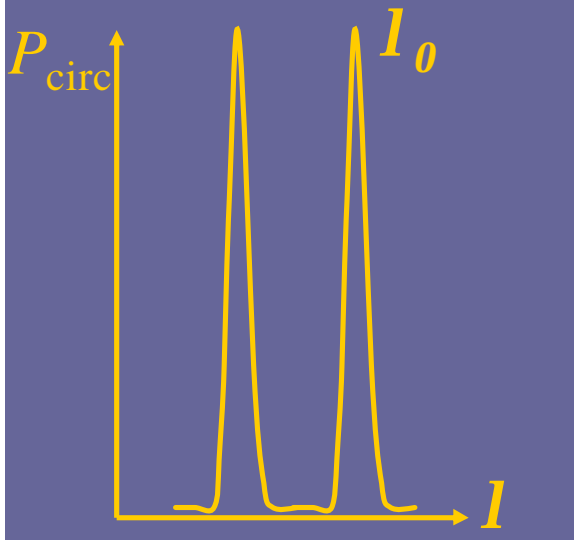
*D. K. Armani et al.* "Ultra-high-Q toroid microcavity on a chip"  
Nature, Volume 421, Feb 2003

$Q \sim 10^6-10^8$   
 $t_p \sim 0.8-80 \text{ ns}$   
 $t_o \sim 0.25-1 \text{ ps}$

# Optical coupling to WG modes



$P_{in} \sim 1 \text{ mW}$ ,  
 $Q \sim 10^8 \Rightarrow$   
 $P_{circ} \sim 100 \text{ W}$

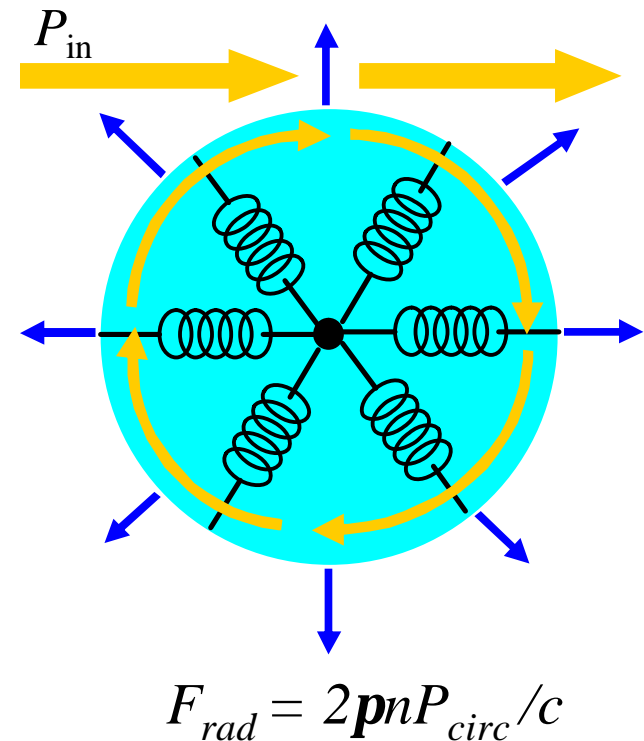
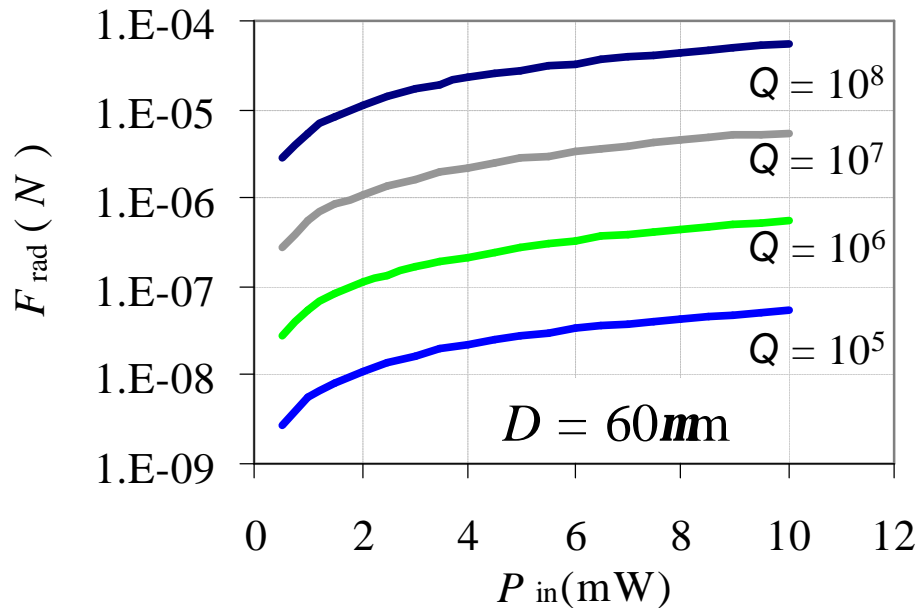


*M. Cai et al.* "Observation of critical coupling in a fiber taper to a silica microsphere whispering-gallery mode system," *Physical Review letters*, Volume 85, pp. 74-77, 2000

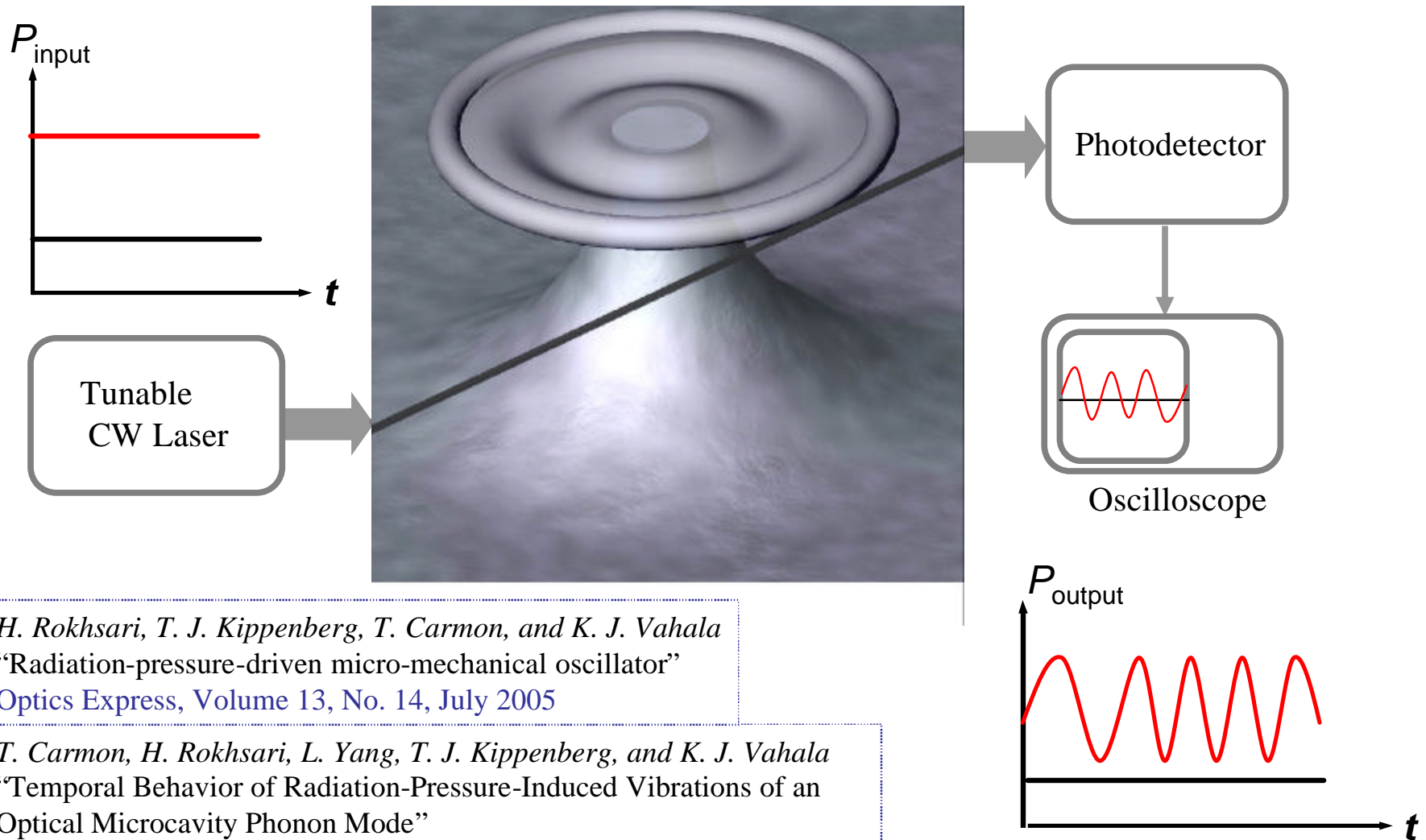
# Radiation pressure in optical cavities

## ◆ Radiation pressure in optical cavities

- ◆ Large circulating power ( $P_{\text{circ}}$ )
  - High optical- $Q$
- ◆ Small spring constant of the structure
  - Small structures



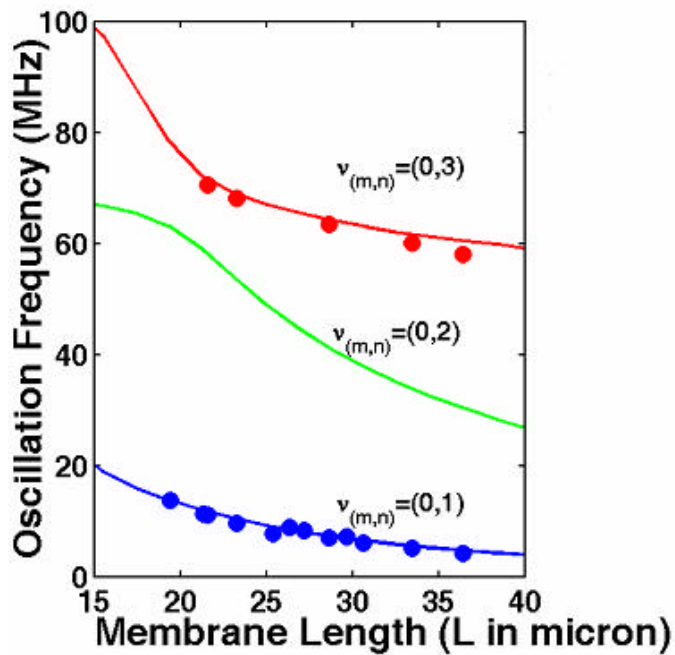
# Experimental observation of Optomechanical oscillation



*H. Rokhsari, T. J. Kippenberg, T. Carmon, and K. J. Vahala*  
"Radiation-pressure-driven micro-mechanical oscillator"  
*Optics Express*, Volume 13, No. 14, July 2005

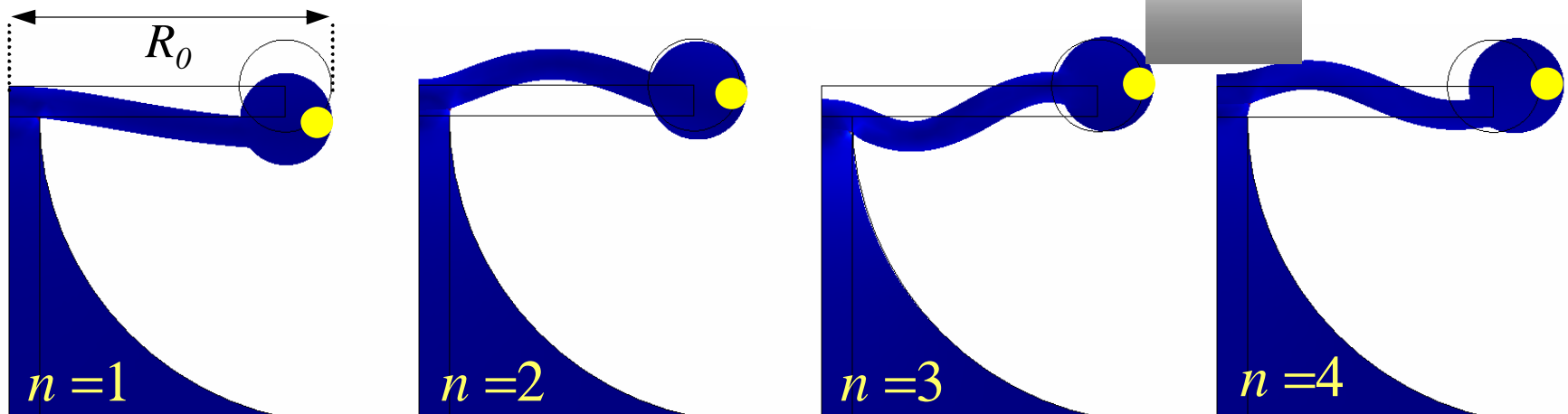
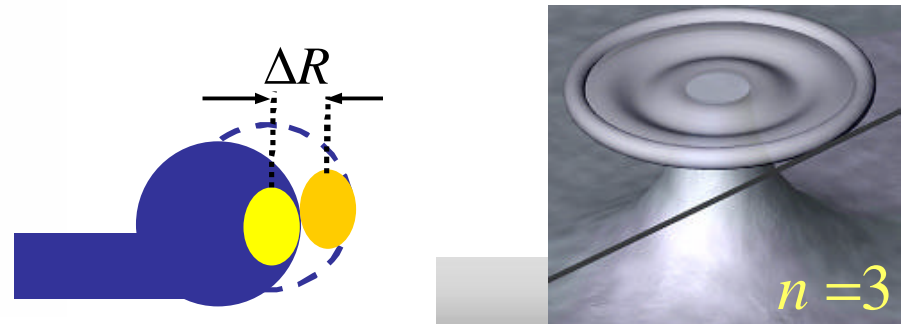
*T. Carmon, H. Rokhsari, L. Yang, T. J. Kippenberg, and K. J. Vahala*  
"Temporal Behavior of Radiation-Pressure-Induced Vibrations of an  
Optical Microcavity Phonon Mode"  
*Physical Review Letters*, Volume 94, 223902, June 2005

# Mechanical modes of a silica microtoroid



$$\frac{d^2 R}{dt^2} + \left(\frac{\Omega_0}{Q_{mech}}\right) \frac{dR}{dt} + \Omega_0^2 R = \frac{F_{rad}}{m_{eff}}$$

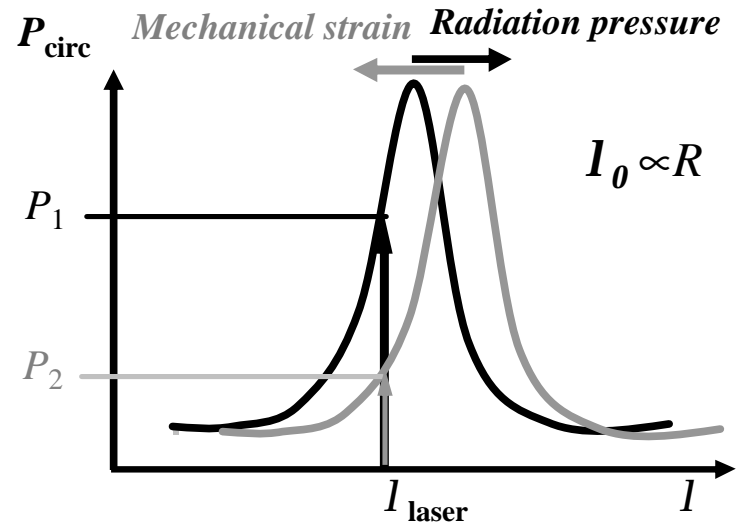
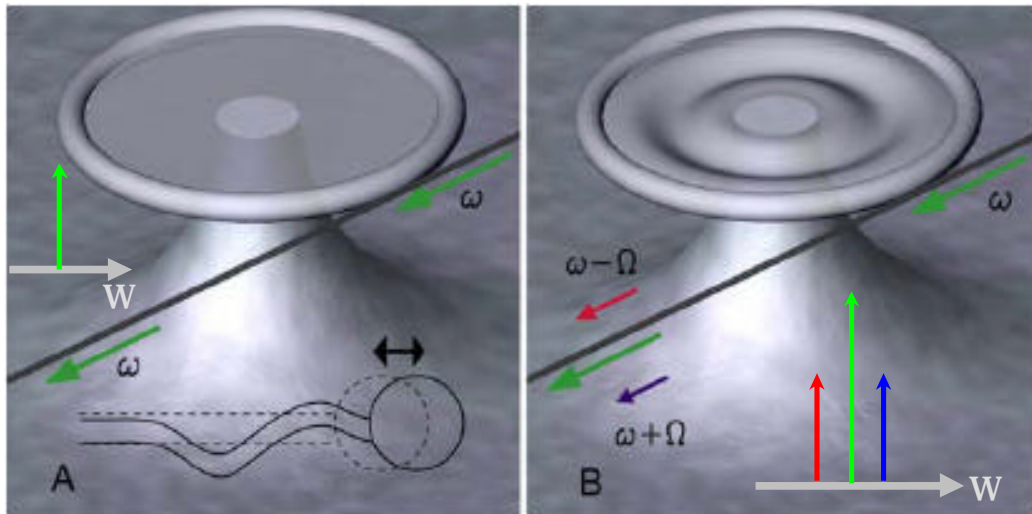
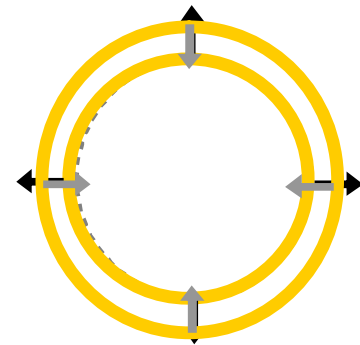
$$m_{eff} = \frac{2E_{mech}}{\Omega_0^2 \Delta R^2} \quad (\text{numerical simulation})$$



# Optomechanical oscillation: mechanism

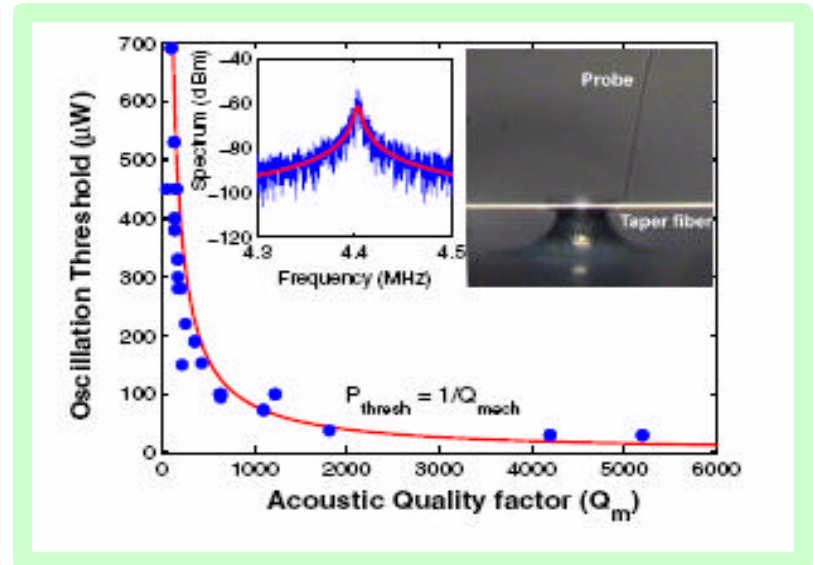
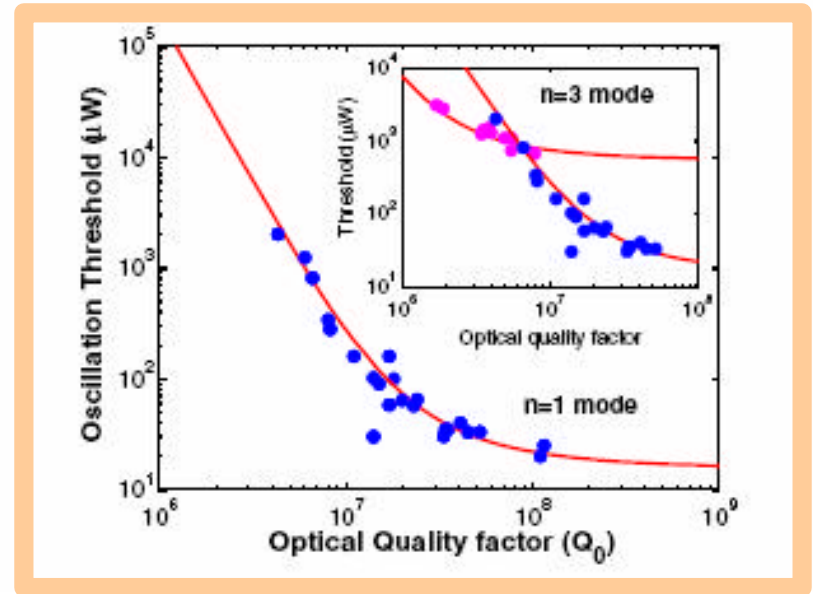
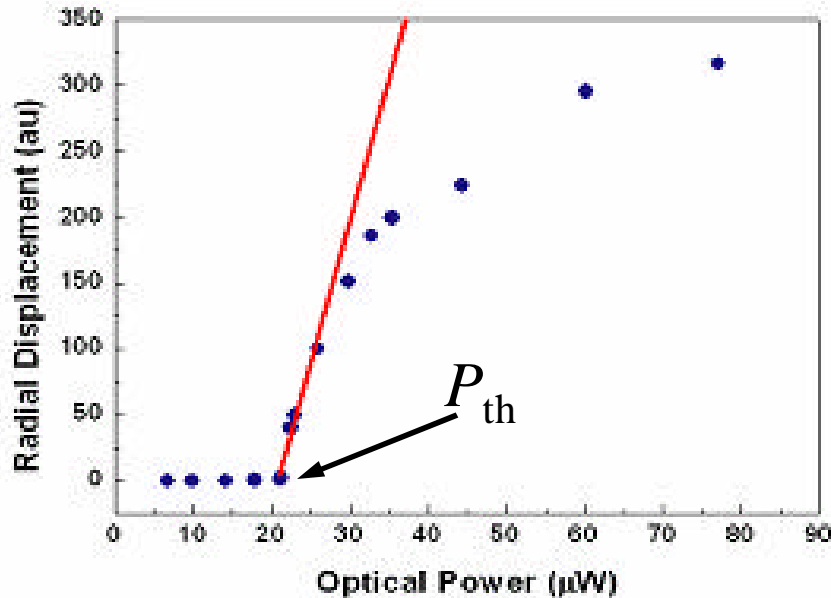
## ◆ Optomechanical coupling between optical and mechanical modes of the microtoroid

- ◆ Inflation : Optical energy  $\rightarrow$  Mechanical energy
  - Red Doppler shift ( $\omega - \Omega_0$ )
- ◆ Deflation : Mechanical energy  $\rightarrow$  Optical energy
  - Blue Doppler shift ( $\omega + \Omega_0$ )



# Threshold power, optical- $Q$ and mechanical- $Q$

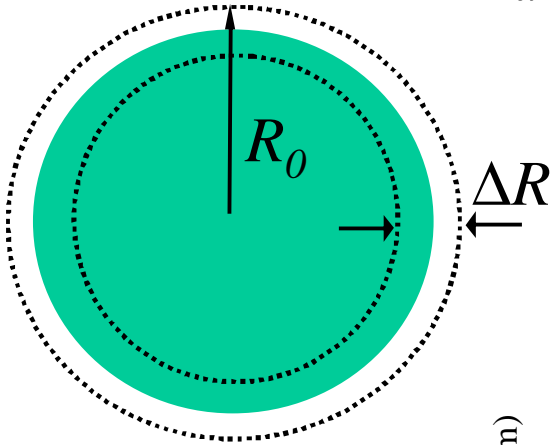
$$P_{th} \propto \frac{\Omega_0}{n_0} \frac{1}{Q_m} \left( \frac{1}{Q_0} \right)^3$$



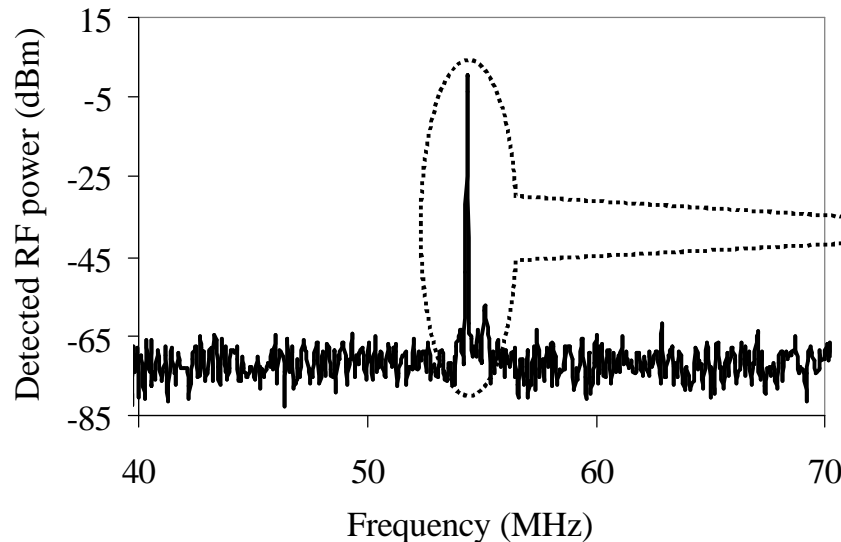
*T. J. Kippenberg, H. Rokhsari, T. Carmon, A. Scherer, and K. J. Vahala* "Analysis of Radiation-Pressure Induced Mechanical Oscillation of an optical Microcavity"  
 Physical Review Letters, Volume 95, 033901, July 2005

# Optomechanical oscillation linewidth

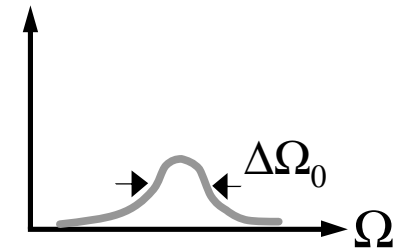
Thermally limited oscillation linewidth  
in a mechanical oscillator



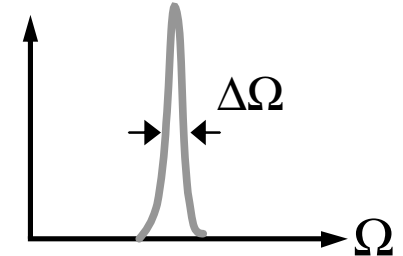
$$\Delta\Omega = \frac{k_B T}{m_{eff} \Omega_0^2} \frac{\Delta\Omega_0}{(\Delta R)^2}$$



$P_{in} \ll P_{th}$



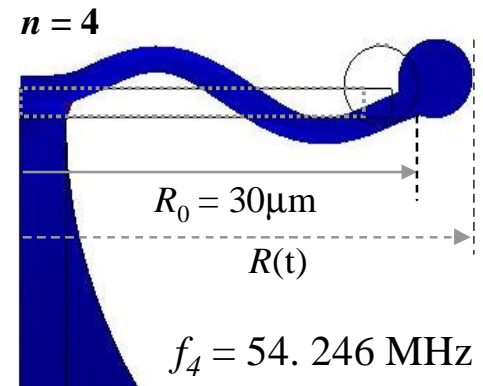
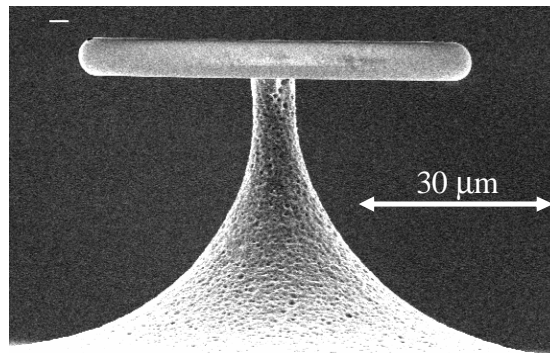
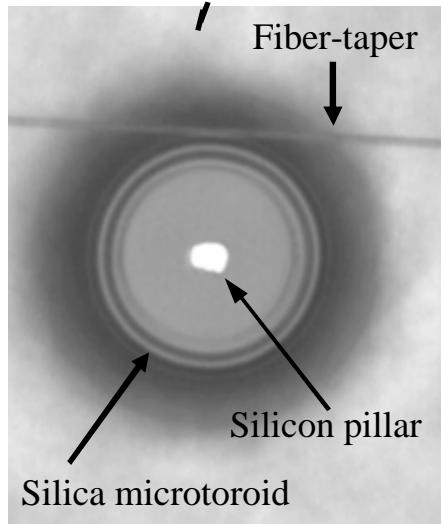
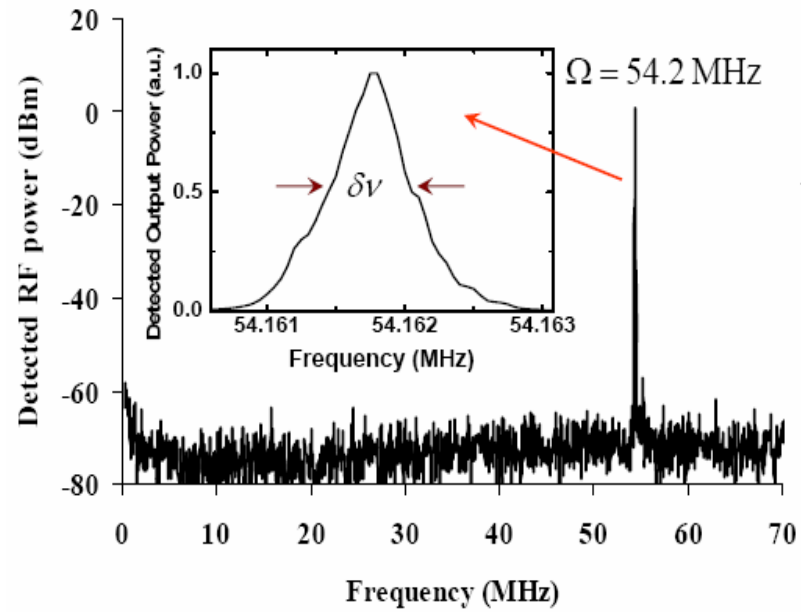
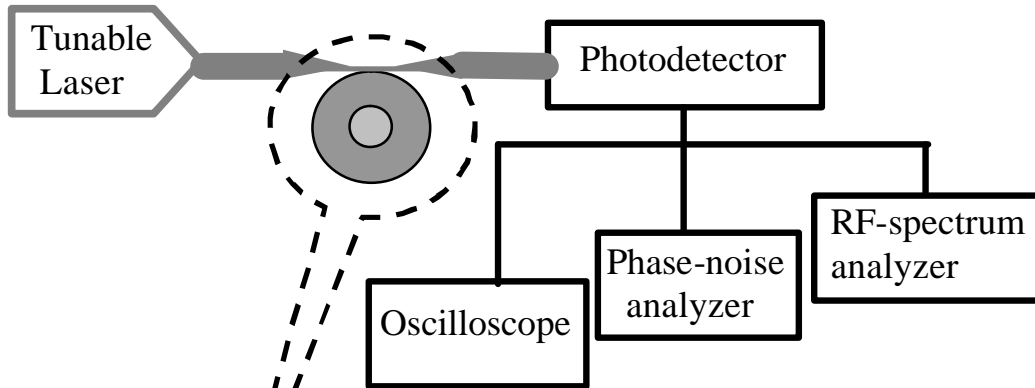
$P_{in} > P_{th}$



W. A. Edson, "Noise in oscillators"

Proceedings of the Radio Engineers, Volume 48, pp. 1454-1466, 1960

# Experiment



# Experimental verification of linewidth narrowing

Phase noise measurement  
(RF Phase noise analyzer)

Linewidth measurement below threshold  
(RF spectrum analyzer)

Regenerative oscillation linewidth

Natural mechanical linewidth

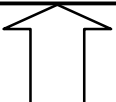
$$\Delta\Omega = \frac{k_B T \Delta\Omega_0}{m_{eff} \Omega^2} \frac{1}{\Delta R^2}$$

Effective mass

Amplitude of the mechanical oscillation

Numerical simulation

Optical modulation depth

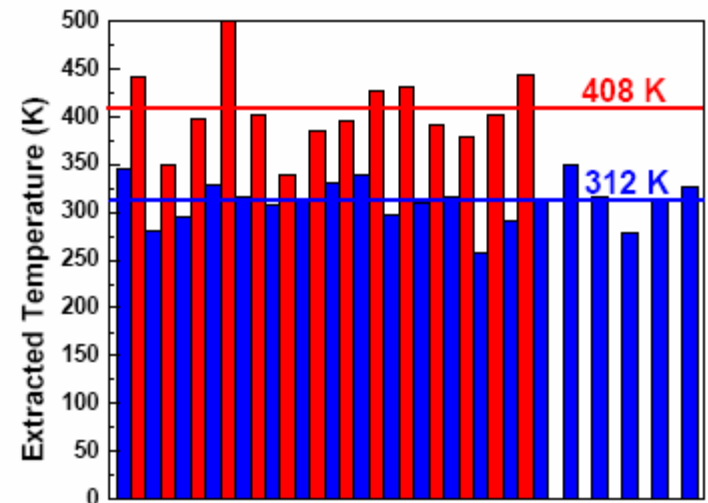
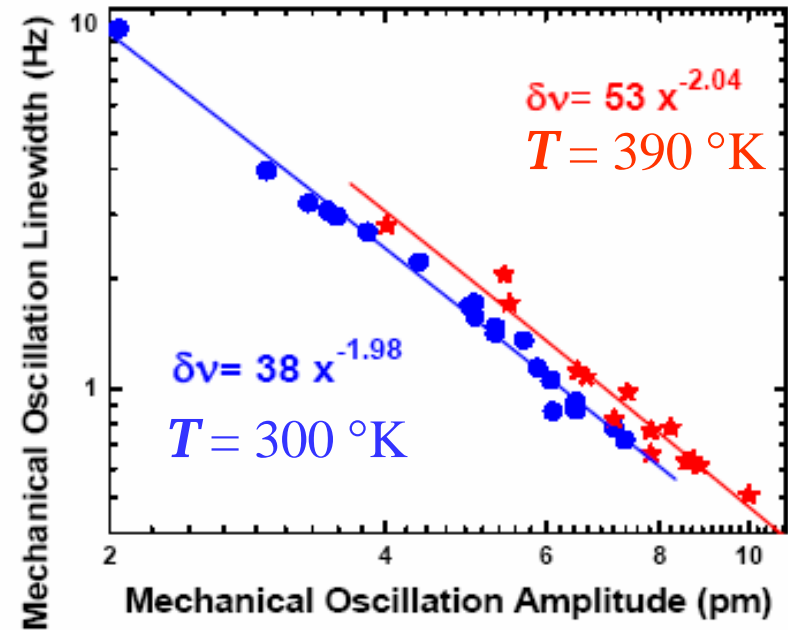


# Experimental results

$$\Delta\Omega \propto \frac{1}{(\Delta R)^2}$$

$$T = \frac{\Delta\Omega}{\Delta\Omega_0} \frac{m_{eff} (\Delta R)^2 \Omega_0^2}{k_B}$$

- ◆ The fundamental linewidth is limited by Brownian noise
  - ◆ Inverse relation with mechanical energy ✓
  - ◆ Temperature dependency ✓



# Summary and outlook

## ◆ All-optical-oscillator

### ◇ Regenerative optomechanical oscillation

- Supports high-Q optical and mechanical modes.
- Provides strong coupling between optical and mechanical modes.

### ◇ Oscillation linewidth

- Sub-Hertz oscillation linewidth
- Linewidth is limited by Brownian noise in the structure.

## ◆ Applications

### ◇ Photonic clock

- Silicon compatible
- Small size

### ◇ New platform for exploring quantum-optical phenomena

- Simplicity
- Small size

Thank you for your attention!

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