

Raman and Optical Parametric Oscillation in Ultra-high-Q Toroid Microcavities

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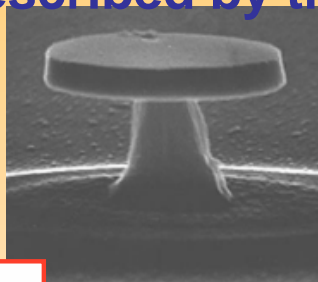
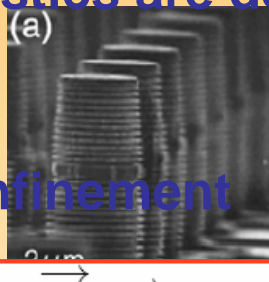


Optical Microcavities

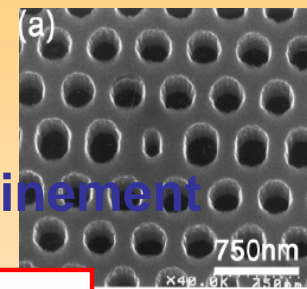
Microcavities confine photons both *spatially* and *temporally*. These two characteristics are described by the Q-factor and Mode-Volume.



Spatial confinement



Temporal confinement



$$V = \frac{\int \epsilon(\vec{r}) |\vec{E}(\vec{r})|^2 d^3r}{\max(|\vec{E}|^2)}$$

$$Q = \omega_0 \tau$$

Micr Micr	Microdisk	Pol	Photonic Crystal
Q: 9×10^9 V: $\sim 1000(\lambda/n)^3$	2,000 $6(\lambda/n)^3$	45,000 $5(\lambda/n)^3$	200,000 $\sim 100(\lambda/n)^3$
<i>Ilchenko, Braginsky (1989)</i> <i>Chang (1989)</i> <i>Kimble (1994)</i>	<i>Juwell, Harbison, Scherer (1991)</i> ...	<i>McCall, Levi, Slusher (1992)</i>	<i>Slusher (1995)</i> <i>Scherer (1998)</i>



Applications of Ultra-high-Q

Cavity QED Strong Coupling (critical atom, critical photon number) [1]	$(n_0 \propto V, N_o \propto \frac{V}{Q}, g_0 \propto \sqrt{\frac{1}{V}})$
Telecommunications Photonics (filter loss, laser threshold) [2]	$\alpha \propto \frac{1}{Q}, 1 - \frac{P_{drop}}{P_{in}} \propto \frac{1}{Q}$
Biochemical sensing [3] (sensitivity)	$S \propto F_{cav} = \frac{\Delta\lambda_{FSR}}{\Delta\lambda_{cav}}$
Cavity Nonlinear Optics (Threshold for oscillation)	$P_{nl} \propto \frac{V}{Q^2}$

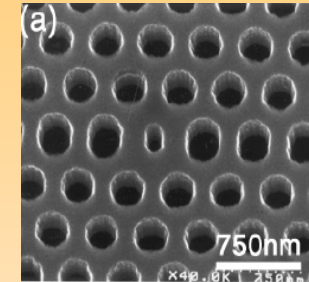
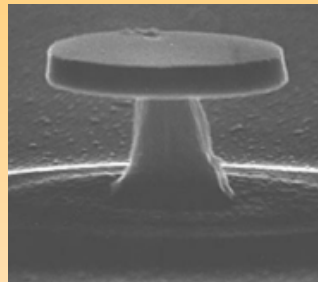
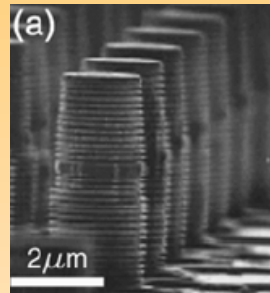
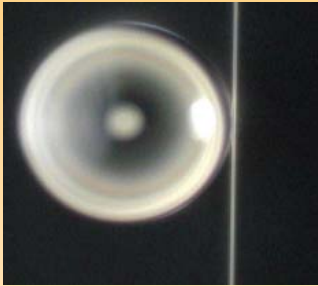
(1) Kimble, Mabuchi, Vernooy (1996), Ilchenko, Gorodetsky, Braginsky (1989), J. Hare S. Haroche (1996)

(2) M. Cai, O. Painter K. Vahala (2001), V. Sandoghdar, V. Lefevre (1995)

(3) Vollmer, Arnold (2002)



Optical Microcavities

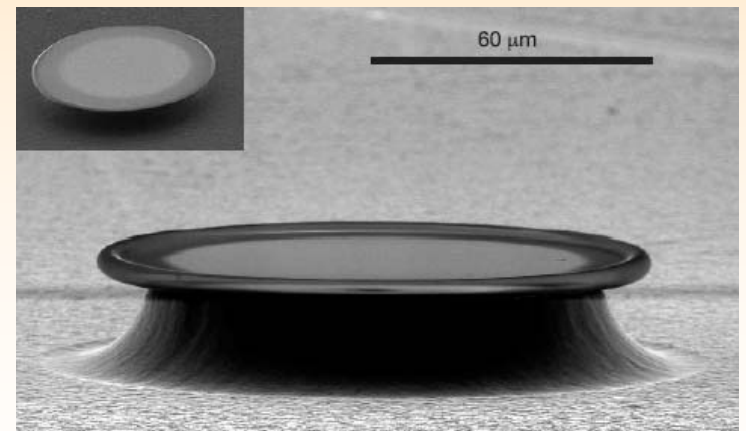
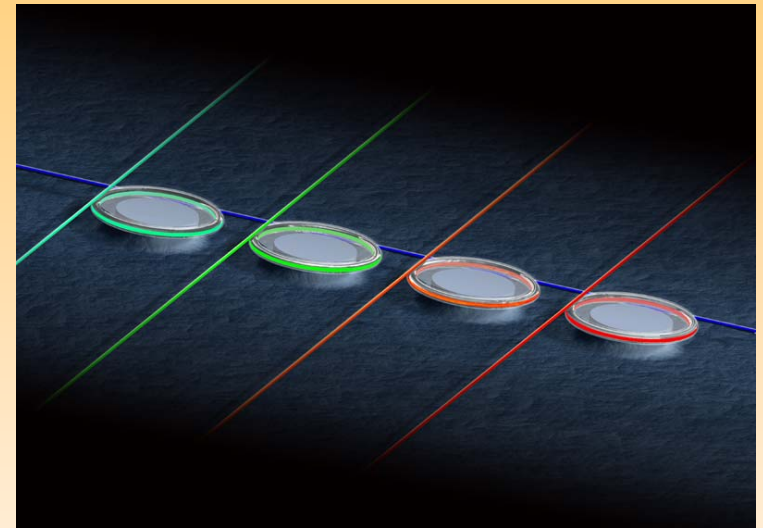


Microdroplet Microsphere	Micropost, (VC)	Microdisk	Polymer-Ring	Photonic Crystal
Q: 9×10^9 V: $\sim 1000(\lambda/n)^3$	2,000 $6(\lambda/n)^3$	45,000 $5(\lambda/n)^3$	200,000 $\sim 100(\lambda/n)^3$	80,000 $(\lambda/n)^3$
<i>Ilchenko, Braginsky (1989) Chang (1989) Kimble (1994)</i>	<i>Juwel, Harbison, Scherer (1991) ...</i>	<i>McCall, Levi, Slusher (1992)</i>	<i>Slusher (1995)</i>	<i>Scherer (1998)</i>



Toroid microcavities on a chip

- **Ultra-high Q-factor**
 - $Q > 10^8$ can be obtained
- **Small mode volume**
- **Highly reduced mode spectrum**
- **Silicon compatible**
 - Built on a silicon wafer
 - Integration with other function

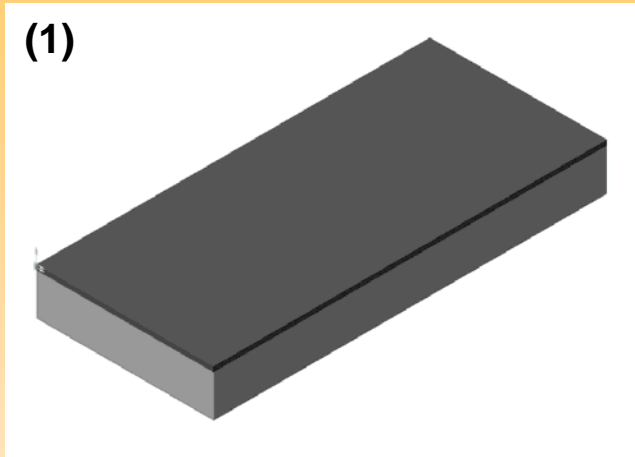


On-chip nonlinear optical oscillators

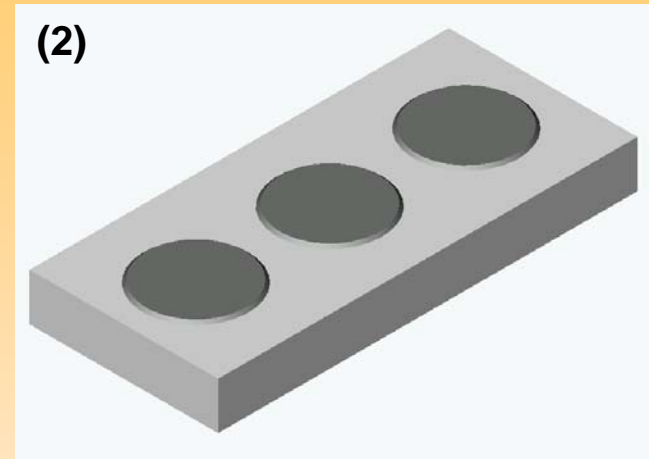


D. K. Armani, T. J. Kippenberg, S. M. Spillane, K. J. Vahala. *Nature* **421**, 925-928 (2003).

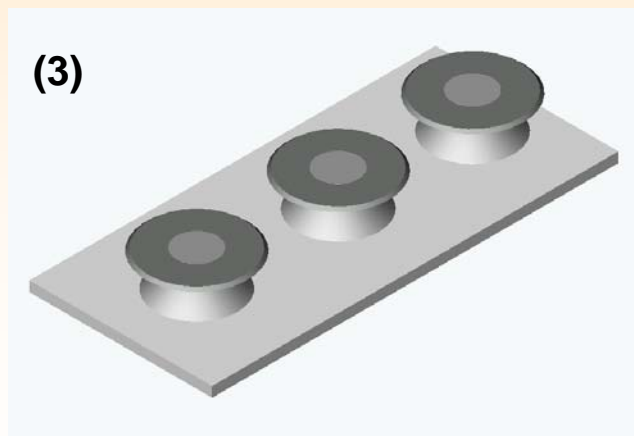
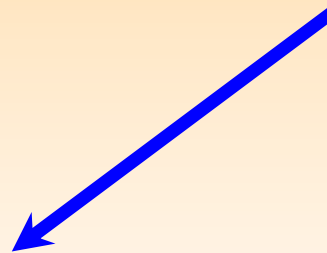
Fabrication of UHQ toroid microcavities



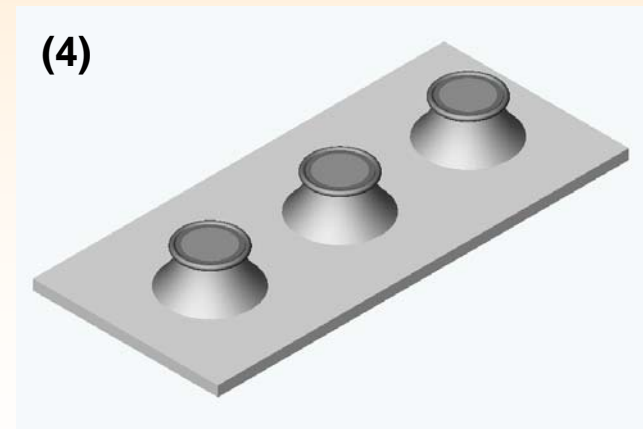
silica film ($2\mu\text{m}$) on a silicon wafer



Silica pads after PR/HF etching



Silica disk resonators after XeF_2 etching



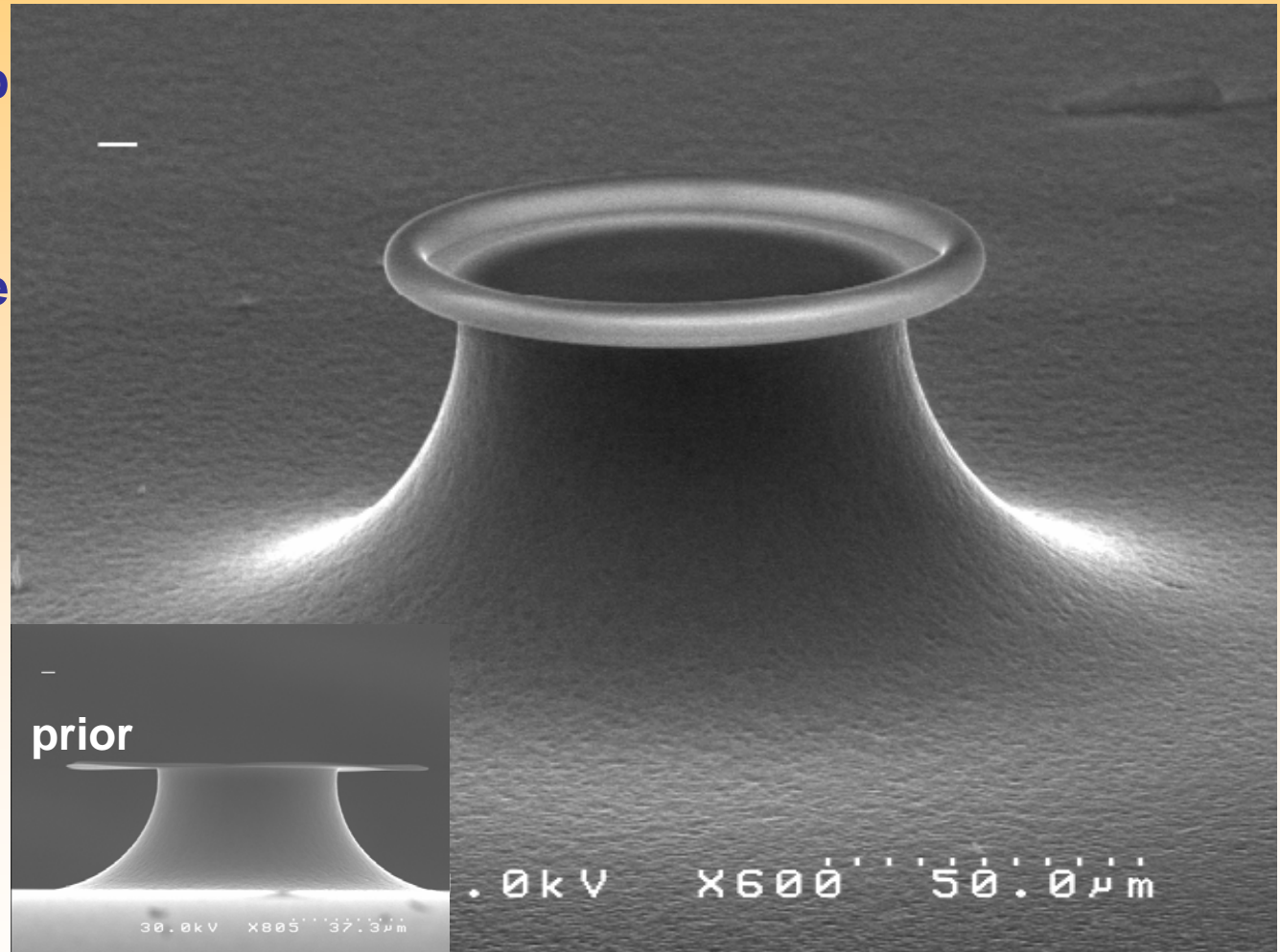
Toroidal microcavities after CO_2 laser annealing



Ultra-high-Q toroid microcavities on a Chip

- Ultra-high-Q modes of up to $Q=400 \times 10^6$
- Chip-based micro-cavity
- Reduced azimuthal mode spectrum
- Small mode volume

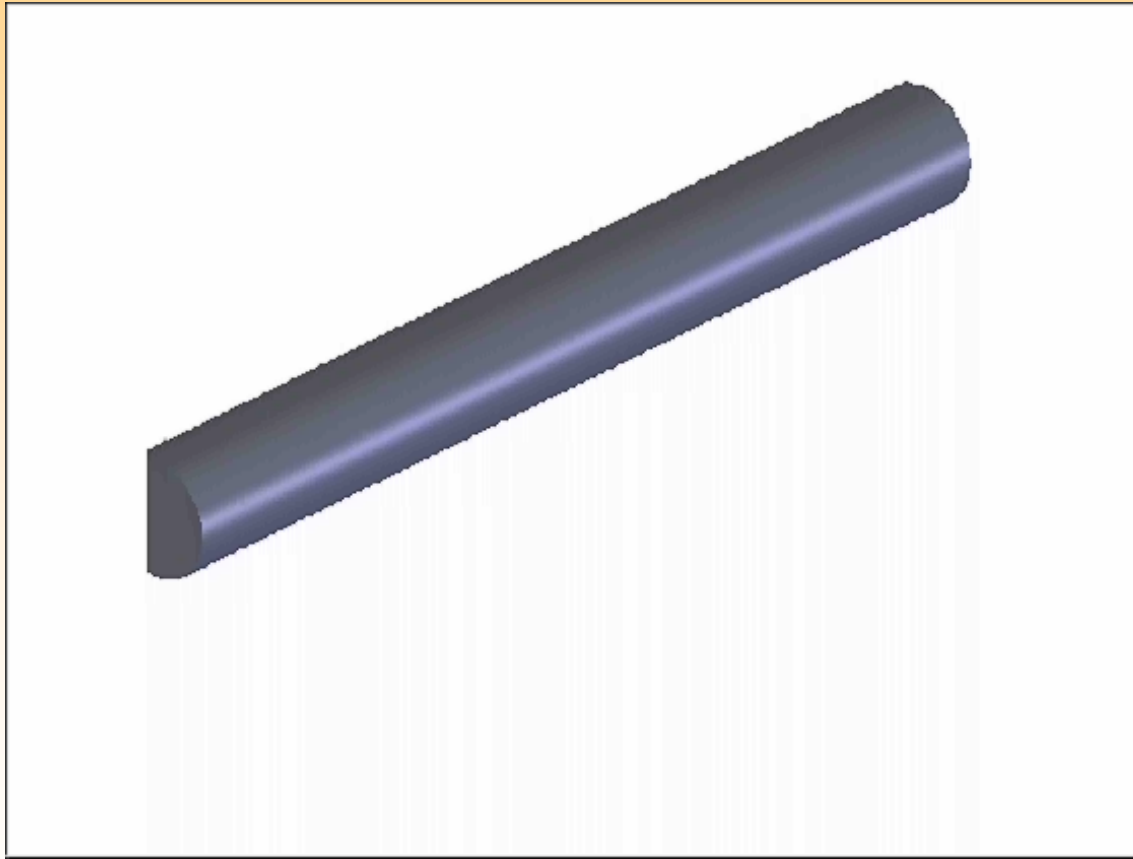
⇒ *Allow integration of nonlinear optical oscillators on a chip.*



Taper fiber coupling

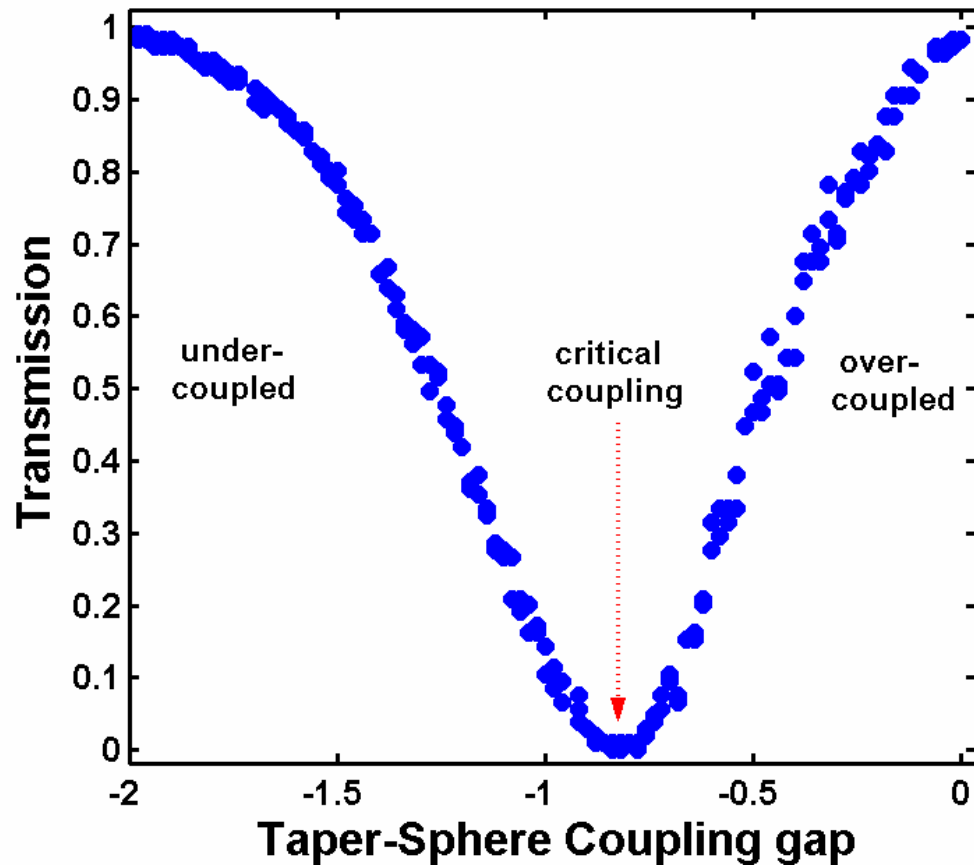
Fiber tapers transition from conventional core guiding regions to air-guiding regions

***SMF-28
fiber***



M. Cai, O.J. Painter, K. J. Vahala. *Phys. Rev. Lett.* (2002).
J. Knight, T.A. Birks, *Optics Letters* (1996)

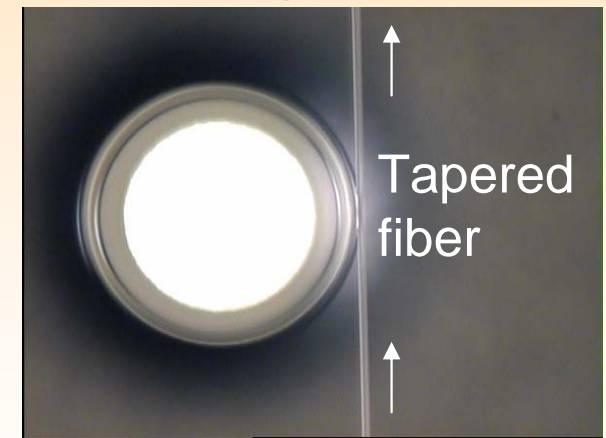
Taper fiber coupling



$\tau_0 < \tau_{ex}$
undercoupled

$\tau_0 = \tau_{ex}$
Critical Coupling

$\tau_0 > \tau_{ex}$
overcoupling

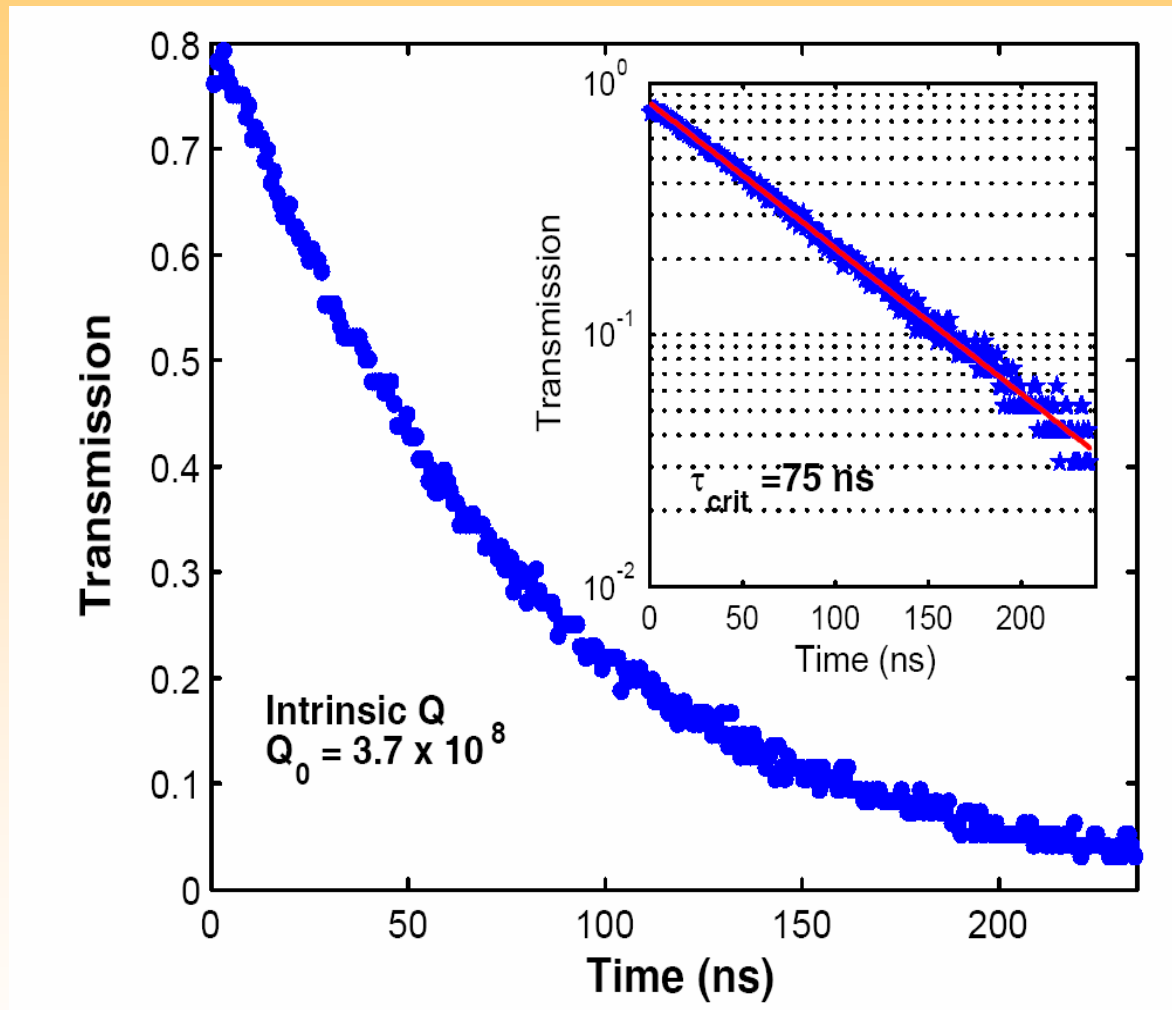


***-taper-microcavity junction induces negligible scattering
exhibits extremely high ideality****

*S. M. Spillane, T. J. Kippenberg, O.J. Painter, K. J. Vahala. *Phys. Rev. Lett.* (2003).



Cavity Ringdown measurements



- **Correction for waveguide loading and modal coupling:**

$$Q_0 = \omega \tau_{crit} (1 + \sqrt{1 + \Gamma^2})$$



Nonlinear optics in UHQ micro-cavities

- Long photon storage times and small mode volume leads to high circulating intensities
- Tapered optical fibers allow ultra-low loss and *optimum* coupling of the micro-cavities

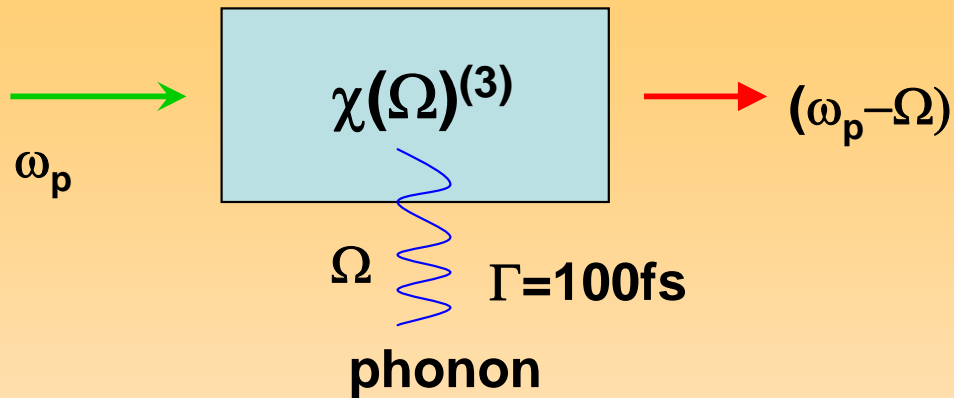
$$\left(\frac{P_{cav}}{P_{in}}\right) = C(\Gamma) \frac{\lambda}{\pi^2 n_{eff} R} \frac{K}{(1+K)^2} Q_0$$

**CAVITY BUILDUP
FACTOR**

$$\begin{array}{l} P_{in} = 1 \text{ mW} \\ V_m \sim 650 \text{ } \mu\text{m}^3 \\ Q \sim 10^8 \\ A_{eff} = 8 \text{ } \mu\text{m}^2 \end{array} \Rightarrow \begin{array}{l} P_{circ} \sim 110 \text{ W} \\ I_{circ} \sim 2.5 \text{ GW/cm}^2 \end{array}$$

NONLINEAR THRESHOLD LEVEL ARE EXCEEDED

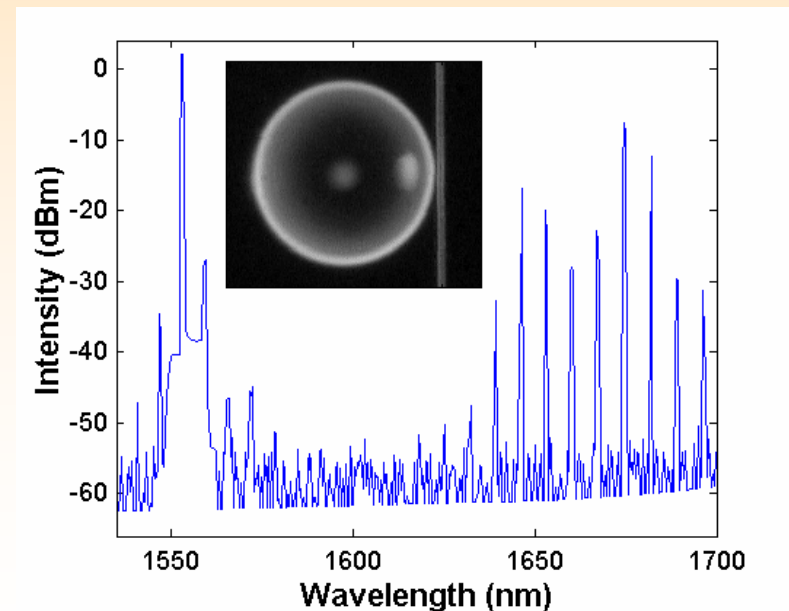
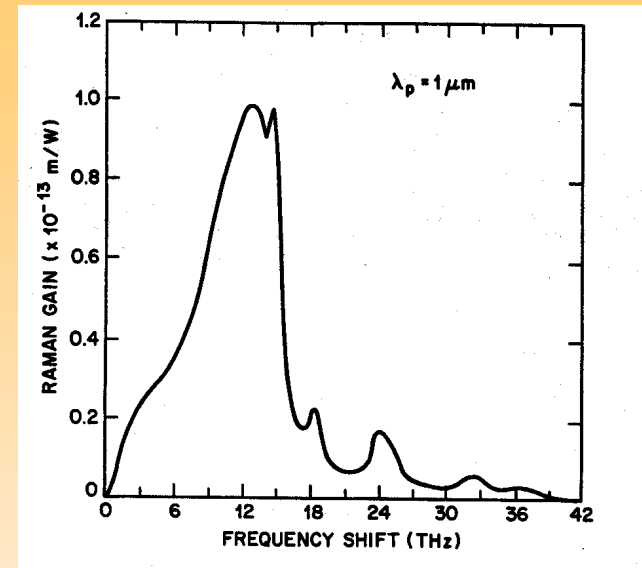
Stimulated Raman Scattering



- Coupling to a dissipative phonon bath
- Phase insensitive amplification
- Intrinsically phase-matched process



- Earliest observed microcavity nonlinear optical effect. (R.K. Chang, A.J. Campillo)
- Microsphere Raman laser* (2004)

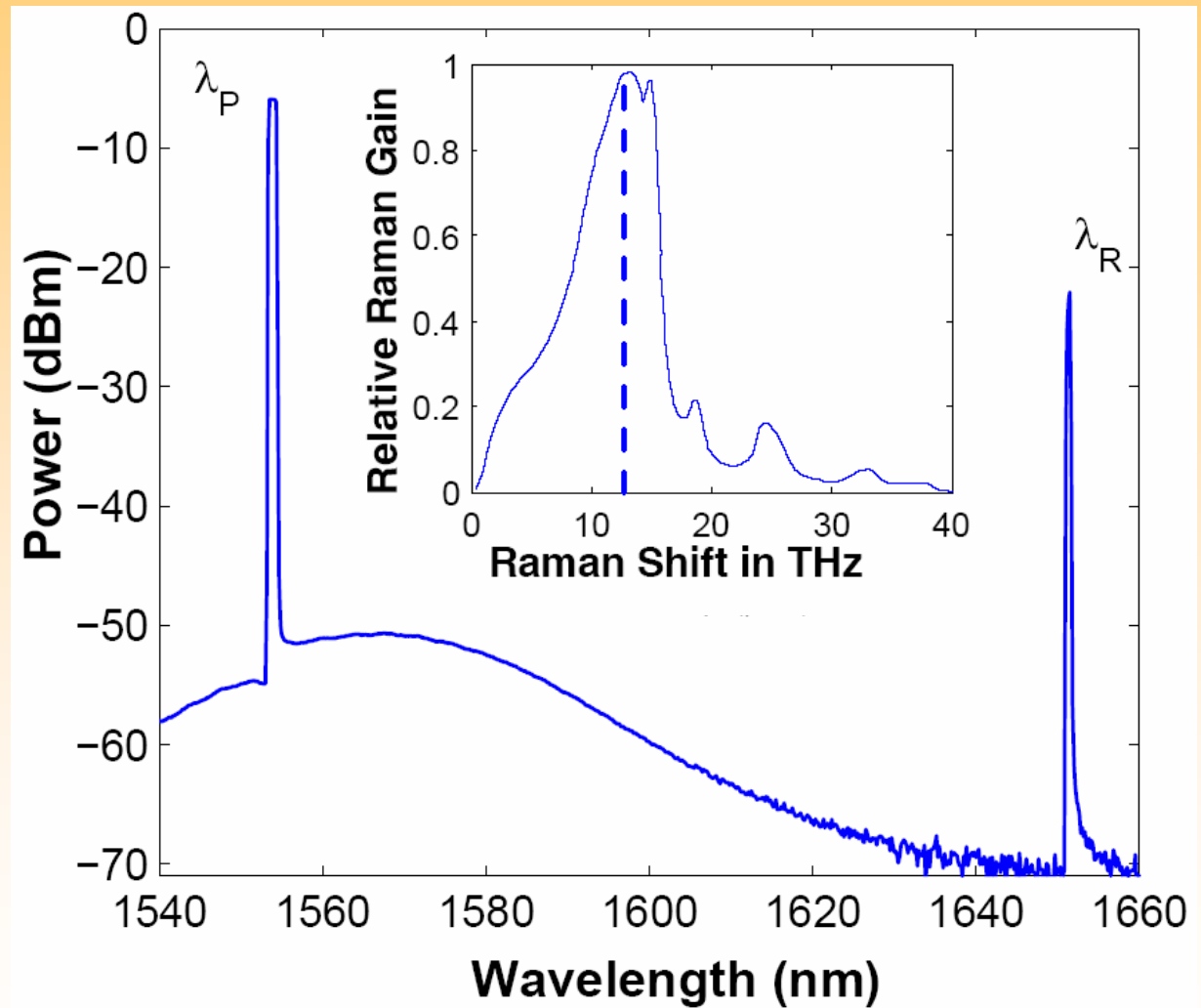


* S. M. Spillane, T. J. Kippenberg, K. J. Vahala. *Nature* **415**, 621-623 (2002).



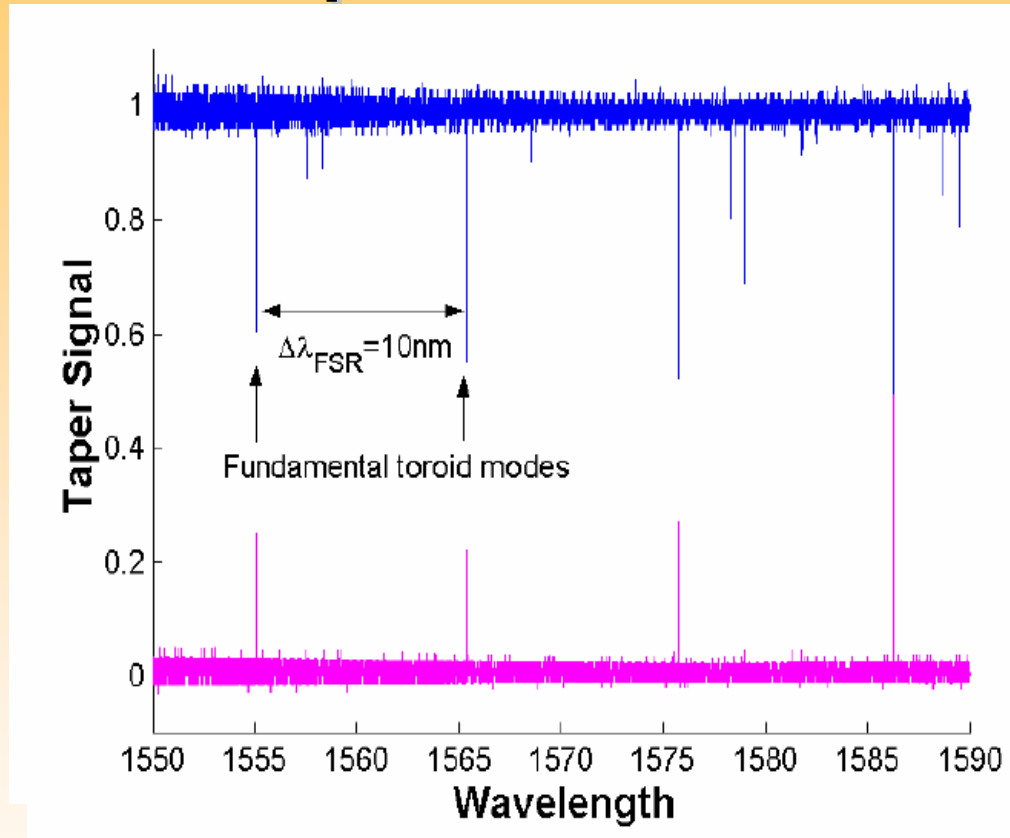
Stimulated Raman Scattering in Ultra-high-Q Toroid Microcavities

- Inherently phase-matched process.
- Threshold levels $P < 100 \mu\text{W}$
- High quantum efficiencies (up to 45%)
- Lower effective threshold
- Single mode emission



T.J. Kippenberg, S.M. Spillane, D.K. Armani, K.J. Vahala, *Optics Letters*, **29** (2004).

Comparison of sphere/toroid mode spectrum



Microsphere Resonator

⇒ Small cross-sectional area toroid microcavities allow significant reduction of number of supported azimuthal modes



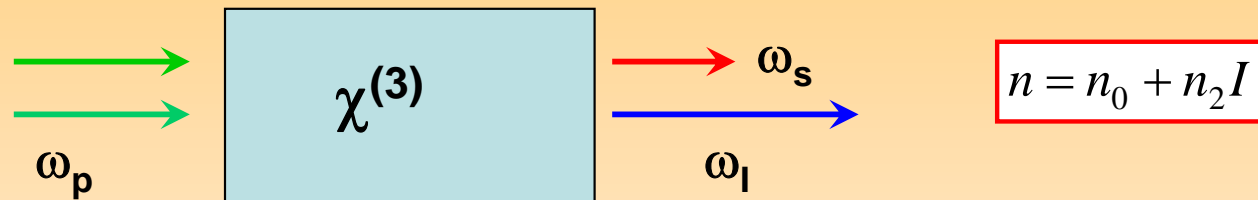
Chip-based Raman oscillators

- Toroid microcavities allow integration of Raman lasers *on chip*
- Ultra-low threshold Raman Lasing
 - Threshold levels $P < 100 \mu W$
- High quantum efficiencies (*up to 45%*)
- *Single mode emission (compared to spherical cavities)*



Nonlinear Optics in Silica microcavities

Parametric Interactions



$$H_{int} = \kappa a_p a_p a_s^\dagger a_I^\dagger + \kappa^* a_p^\dagger a_p^\dagger a_s a_I$$

- Mediated by the Kerr-nonlinearity
- Energy conservation
- Momentum conservation
- Phase sensitive amplification



Significance of Optical Parametric Interactions

- **Optical parametric interactions are energy and momentum conserving processes.**
- **Phase-sensitive amplification scheme**



- **Application of Kerr-Parametric Interactions:**
 - **Quantum Information Theory**
 - **Generation of entangled photon states (G. Leuchs, MPI),**
 - **Quantum Optics**
 - **Quadrature squeezing (Levenson, Shelby, Perlmutter, IBM),**
 - **Two mode squeezing (P. Kumar, Northwestern),**
 - **Solitons, optical switching, quantum measurements...**

• **Stimulated nonlinear phenomena have been observed in a microcavity, for over two decades.**

• **First report of disk-cavity optical Parametric Interaction (Ilchenko, PRL, 2004)**



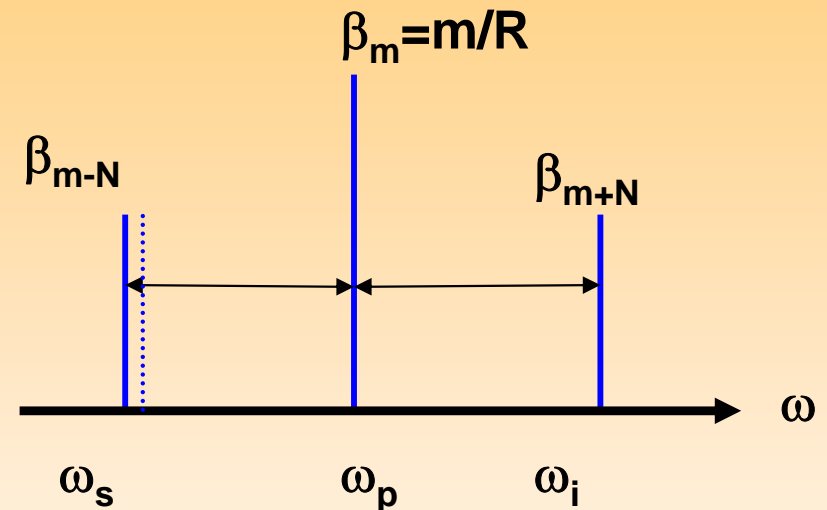
Parametric Oscillation: Momentum Conservation in a microcavity

(Angular) Momentum conservation

$$2\beta_p - \beta_S - \beta_I = \Delta\beta$$

• ***intrinsically satisfied*** for WG modes with angular mode numbers spaced symmetrically

$$\beta_S = \beta_{m-N} \text{ and } \beta_I = \beta_{m+N}$$



Propagation constant of a WGM:

$$\beta_m = \frac{m}{R_0}$$



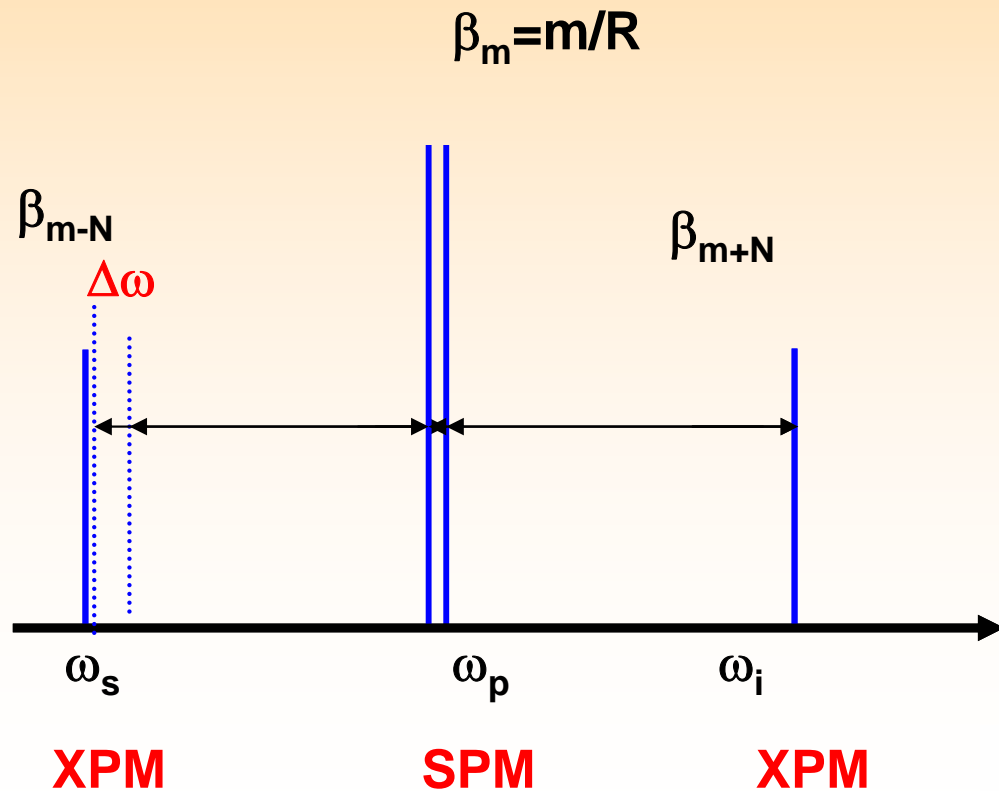
Energy Conservation in a microcavity

Energy conservation requires:

- In a cavity the resonant-frequencies are *discrete* and in general also *irregularly spaced*

$$\Delta\omega = 2 \cdot \omega_p - \omega_s - \omega_I$$

- Cross-phase-modulation (XPM)** and **Self-phase modulation (SPM)** which effectively “pull the modes” into resonance.



$$\Delta\omega < \Omega = 4 \cdot \frac{c}{n} \gamma P$$

$$\gamma = \frac{n_2}{c} \frac{\omega}{A_{eff}}$$

$$n = n_0 + I \cdot n_2$$



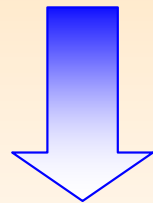
Competition between Kerr and Raman processes

Parametric Oscillation Threshold

$$P_t^K = \frac{\omega_0^2 Q_0^{-2} (1 + K)^2 + (\Delta\omega/2)^2}{2\gamma\Delta\omega (c/n_{eff})} \cdot \frac{\pi^2 R n_{eff}}{C(\Gamma)\lambda_0} \frac{1}{Q_0} \frac{(K + 1)^2}{K}$$

Raman Oscillation threshold

$$P_t^R = \frac{\pi^2 n^2}{C(\Gamma)g_R\lambda_p\lambda_R} V_{eff} \cdot \left(\frac{1}{Q_0}\right)^2 \frac{(1 + K)^3}{K}$$



Max. Raman and Max. Parametric gain $g_{Kerr} \approx 2 \times g_{Raman}$

\Rightarrow **Parametric Regime** $P_{Param}(\Delta\omega, K) < P_{Raman}$

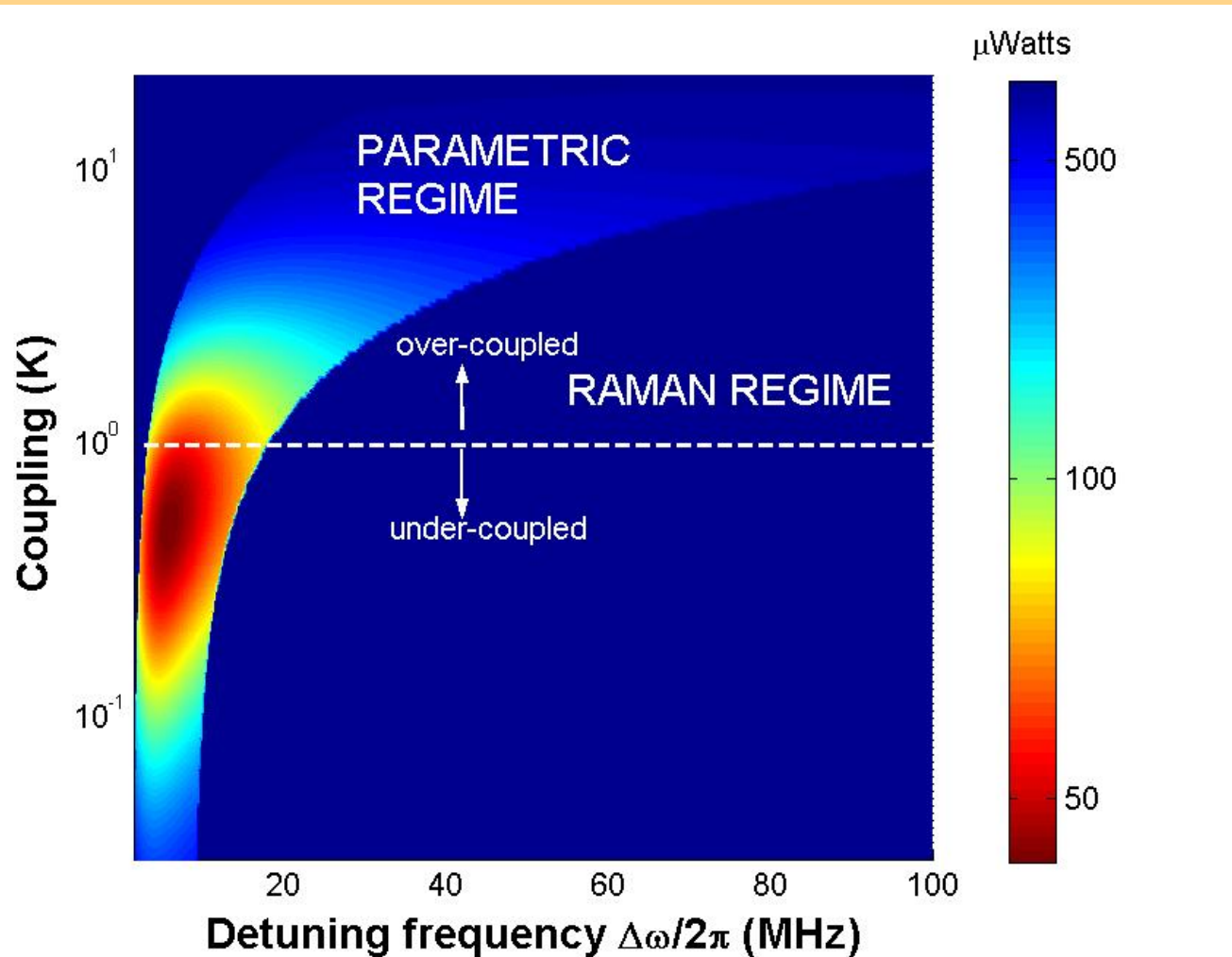
\Rightarrow **Raman Regime** $P_{Param}(\Delta\omega, K) > P_{Raman}$

\Rightarrow Map of microcavity nonlinear optical processes



Map of Microcavity Nonlinear Optical Processes

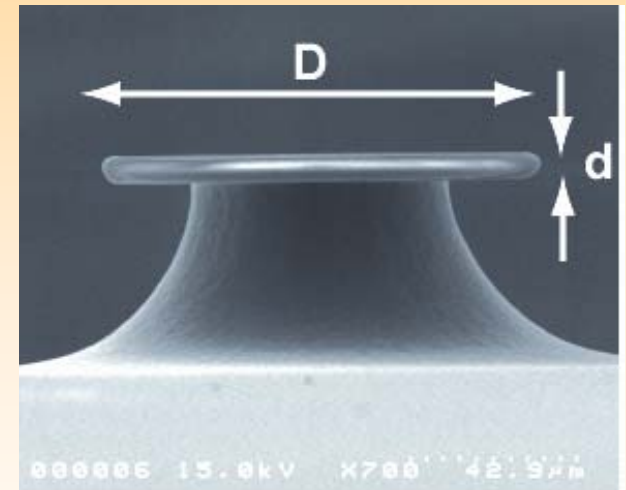
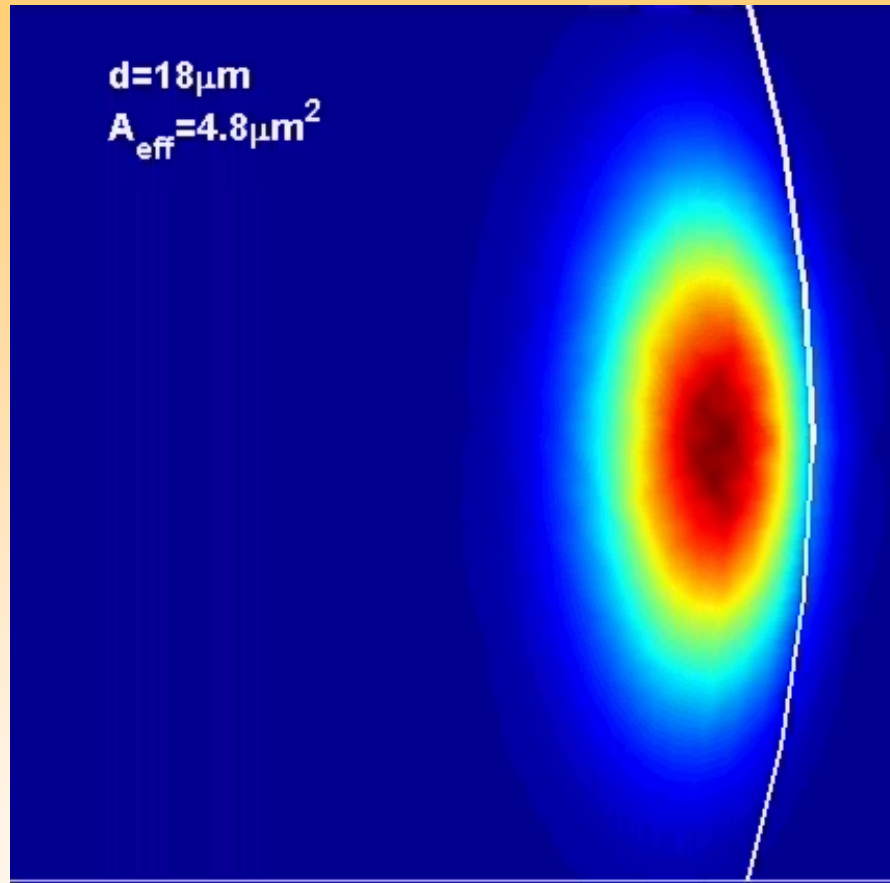
- Nonlinear optical processes in a $Q_0=1 \times 10^8$, $D=50 \mu\text{m}$ $d=4 \mu\text{m}$ microcavity geometry



- **Control over $\Delta\omega$ is required to achieve transition to parametric regime.**



Parametric Bandwidth of a toroid



$$\gamma = \frac{n_2 \omega}{c A_{\text{eff}}}$$

Toroid with small cross sectional area:

⇒ Parametric Bandwidth is increased

⇒ Intrinsic mode dispersion is reduced



Parametric Bandwidth and Modal dispersion of a toroid

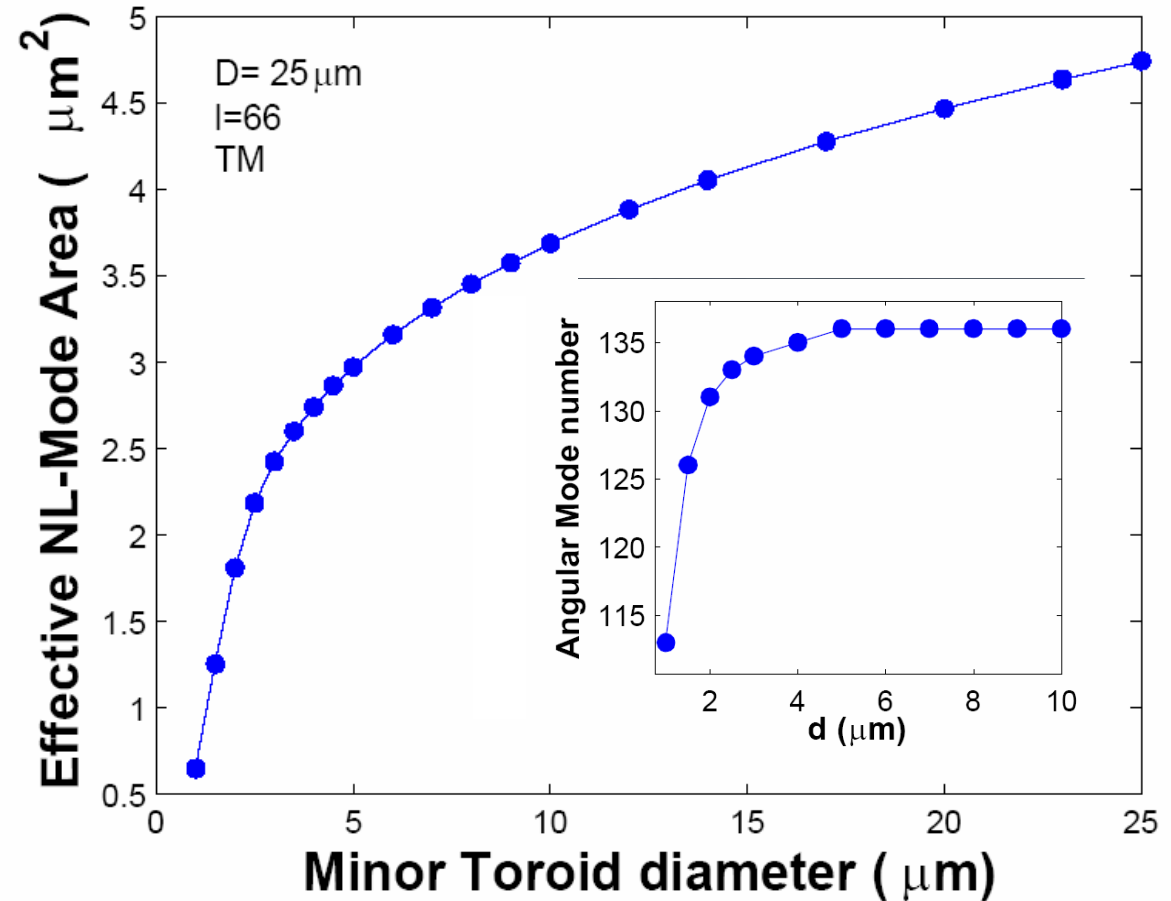
1. \Rightarrow Parametric Bandwidth is increased

$$\gamma = \frac{n_2}{c} \frac{\omega}{A_{eff}}$$

$$\Delta\omega < \Omega = 4 \cdot \frac{c}{n} \gamma P$$

2. \Rightarrow Intrinsic mode dispersion is reduced

$$n_{eff} = \frac{\beta_m}{k_0} = \frac{m}{k_0 R_0}$$



\Rightarrow Small cross sectional area toroids exhibit:

- Increased parametric bandwidth

- Decreased dispersion

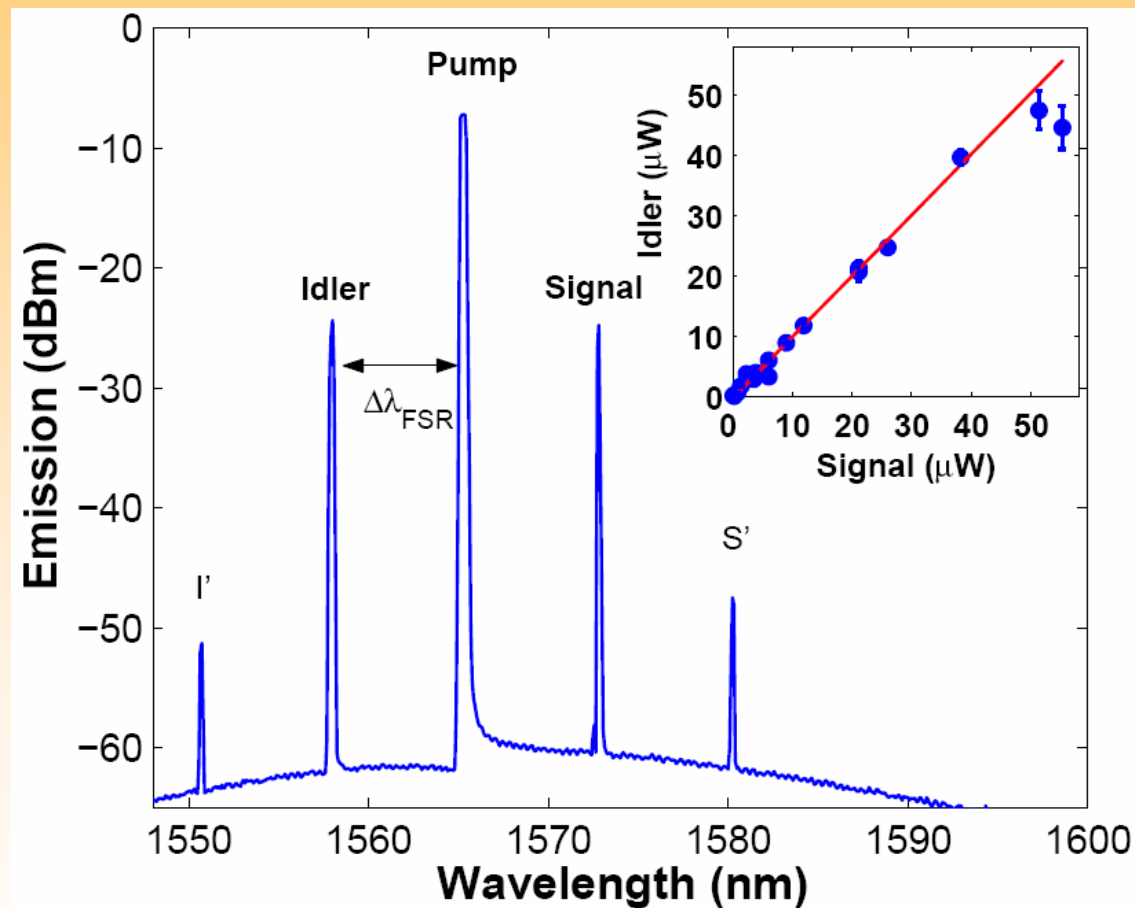


Optical Parametric Oscillation

- Near unity signal-to-idler ratio observed

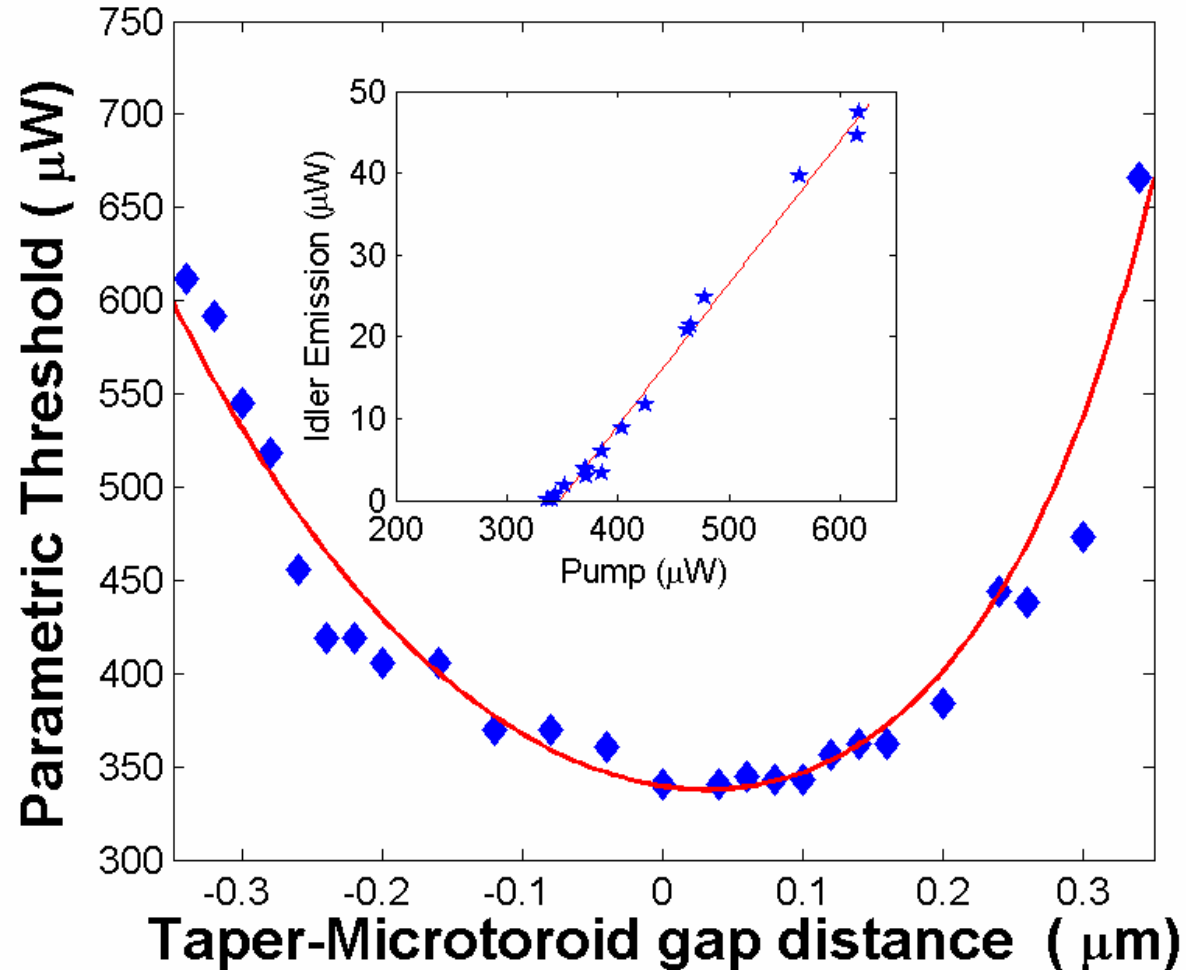
- Up to 40 μW of parametric power

⇒ First observation of Kerr-optical parametric oscillation in a microcavity.



T.J. Kippenberg, S.M. Spillane, K.J. Vahala, *Physical Review Letters* (accepted June 2004)

Optical Parametric Threshold



⇒ *Minimum threshold occurs undercoupled*

⇒ *Inferred cavity detuning <20 MHz*

Lowest threshold 175 μW



Summary

- **Chip based oscillators**
 - Raman laser
 - OPOs
- **A transition from stimulated Raman to Optical parametric oscillation**
- **First demonstration of a micro-cavity Kerr-nonlinearity optical parametric oscillator**
- **Highly efficient, and low threshold μ OPO.**
- **Near unity signal-to-idler ratio**

Acknowledgements:

- **DARPA, NSF, Caltech Lee-Center for Advanced Networking**

www.its.caltech.edu/~vahalagr

