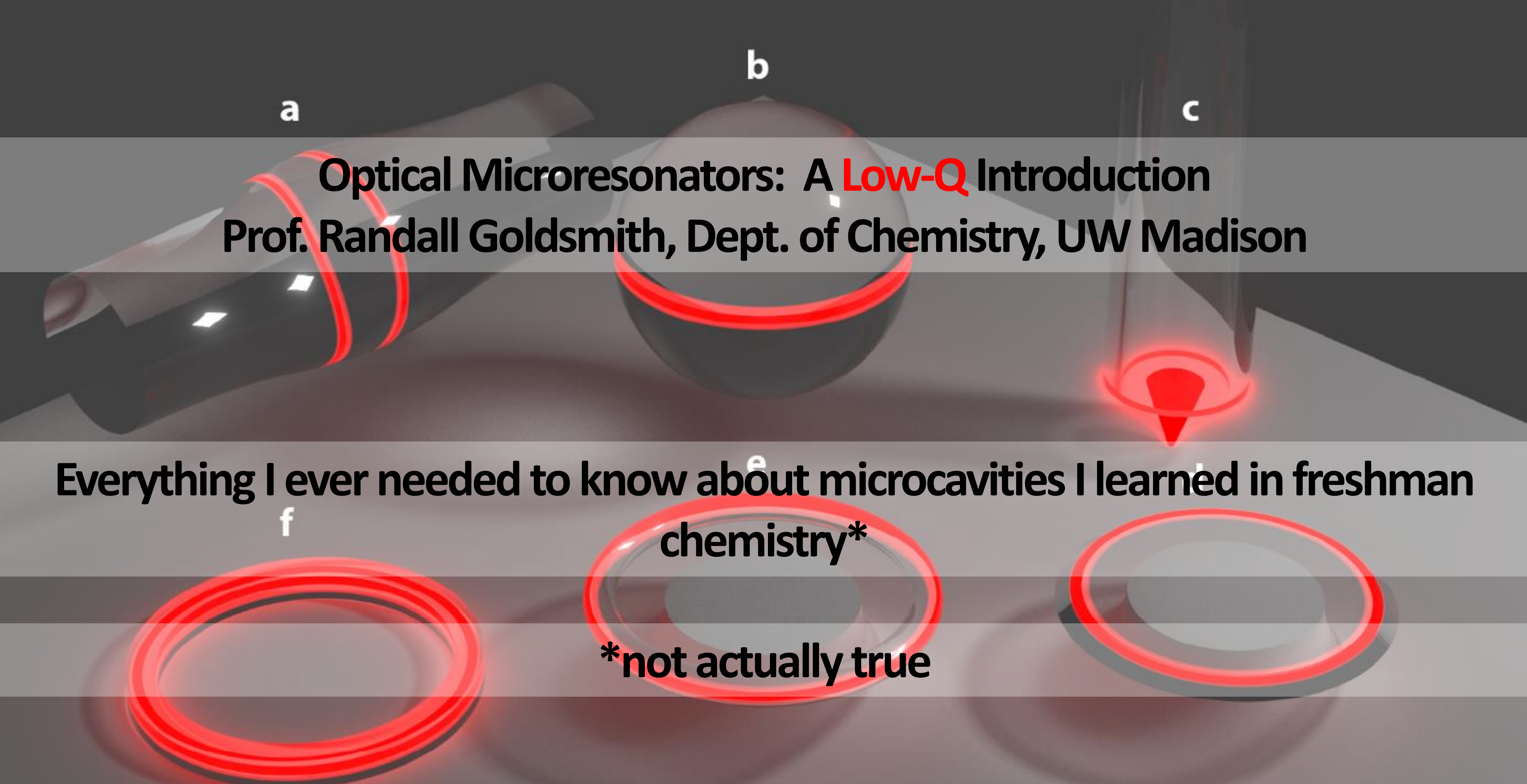


Optical Microresonators: A Low-Q Introduction

Prof. Randall Goldsmith, Dept. of Chemistry, UW Madison

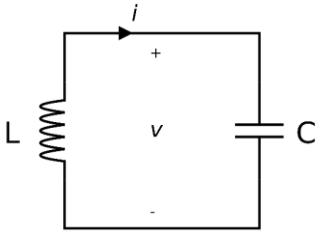
Everything I ever needed to know about microcavities I learned in freshman chemistry*

*not actually true

“Optical microresonators for sensing and transduction: a materials perspective”, *Advanced Materials*, **2017**, 30, 1700037.

Equations of Motion

LC circuit



$$\boxed{\frac{\partial^2}{\partial t^2}v + \omega^2 v = 0}$$

$$\omega = \sqrt{\frac{1}{LC}}$$

Electromagnetic Waves

Wave Equation (isotropic, non-polarizable media)

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E} = 0$$

$\vec{E}$=A(x,y,z)Y(t)

$\vec{E}$= $\sum_{mode\#'s}$ A(x,y,z)Y(t)

Helmholtz Eq

$$\nabla^2 \vec{A} + k^2 \vec{A} = 0$$

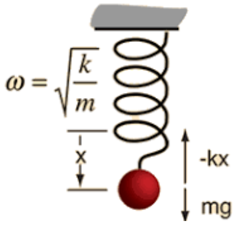
$$\boxed{\frac{\partial^2}{\partial t^2}Y + \omega^2 Y = 0}$$

$\omega = kc$

$$k = \frac{2\pi}{\lambda}$$

Spatial modes (later)

Mechanical Harmonic Oscillator

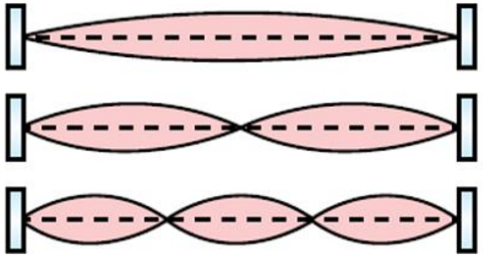


$$\boxed{\frac{\partial^2}{\partial t^2}x + \omega^2 x = 0}$$

$$\omega = \sqrt{\frac{k}{m}}$$

Multiple longitudinal modes

$$\omega = \frac{\pi c m}{(n)L}$$



$\vec{E}$(x=0)=$\vec{E}$(x=L)=0
(perfect conducting walls)

Haus, “Waves and Fields in Optoelectronics”, 1984, Prentice-Hall

The Quality Factor

$$\frac{\partial^2}{\partial t^2}Y + \omega^2 Y = 0$$

$$Y = Ae^{i\omega t}$$

$$\frac{\partial}{\partial t}Y = i\omega Y$$

$$|Y|^2 \propto energy$$

But what if your resonator isn't perfect? What if there's loss?

$$\frac{\partial}{\partial t}Y = i\omega Y - \frac{1}{2\tau_0}Y$$

$$Y = Ae^{i\omega t - \frac{1}{2\tau_0}t} = Ae^{i\omega t}\, e^{-\frac{1}{2\tau_0}t}$$

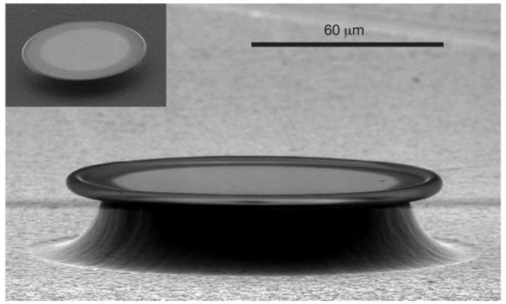
$$\frac{\partial}{\partial t}|Y|^2 = -\frac{1}{\tau_0}|Y|^2$$

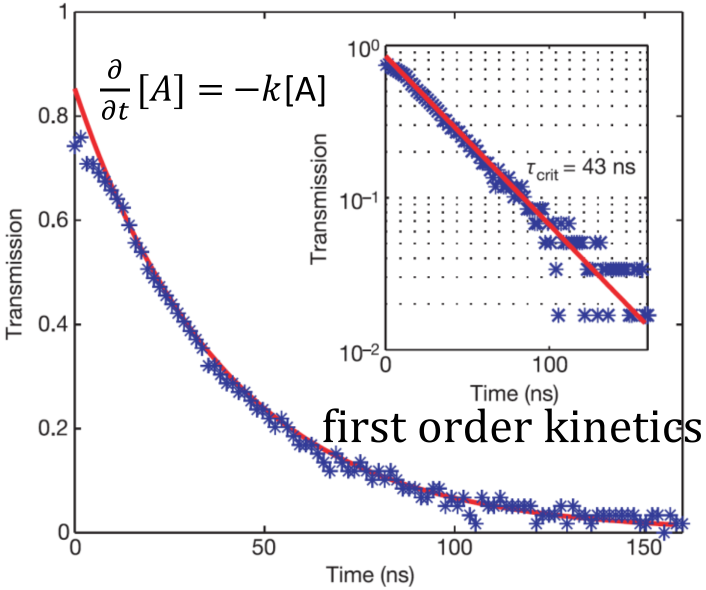
Quality Factor

$$Q = \tau_0 \omega$$

What could cause Q to drop?

Absorption, scattering, radiative losses, waveguides





$$\frac{\partial}{\partial t}[A] = -k[\mathrm{A}]$$

first order kinetics!

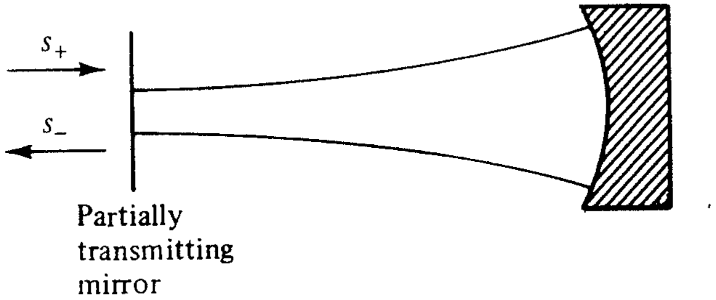
Vahala and co-workers, Nature, 2003, 421, 925,

Haus, "Waves and Fields in Optoelectronics", 1984, Prentice-Hall

Coupling to Your Microcavity

$$\frac{\partial}{\partial t}Y = i\omega Y - \frac{1}{2\tau_0}Y$$

Add an "empty" external waveguide or partially transmitting mirror



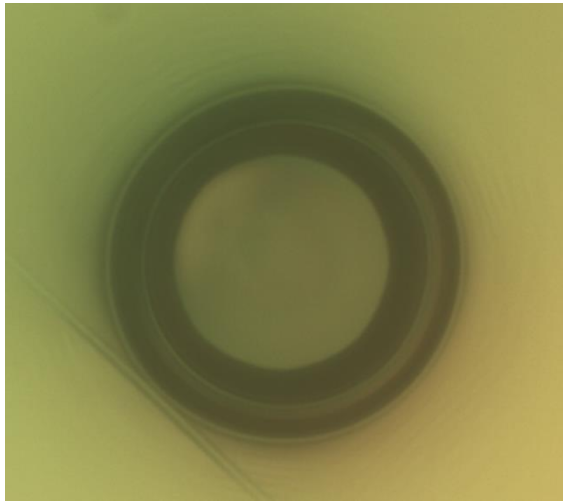
$$\frac{\partial}{\partial t}Y = i\omega Y - \left(\frac{1}{2\tau_0} + \frac{1}{\tau_e}\right)Y$$

Launch a travelling wave at frequency ω_e into that waveguide with power $|s_+|^2$

$$\frac{\partial}{\partial t}Y = i\omega Y - \left(\frac{1}{2\tau_0} + \frac{1}{\tau_e}\right)Y + \kappa s_+$$

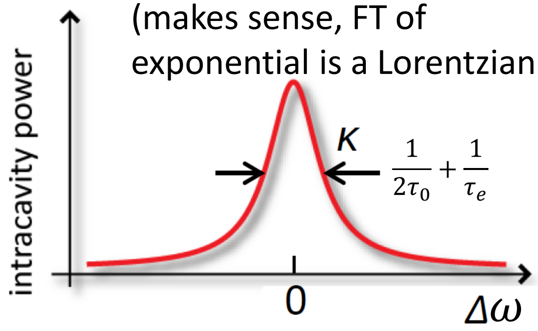
$$s_+ = Be^{i\omega_e t}$$

Use that input wave to "measure" the response of the microcavity as a function of ω_e



$$\frac{\partial}{\partial t}Y = i\omega Y - \left(\frac{1}{2\tau_0} + \frac{1}{\tau_e}\right)Y + \sqrt{\frac{2}{\tau_e}}s_+$$

$$|\bar{Y}|^2 = \frac{\frac{1}{\tau_e}}{(\omega - \omega_e)^2 + \left(\frac{1}{2\tau_0} + \frac{1}{\tau_e}\right)^2}|\overline{s_+}|^2$$



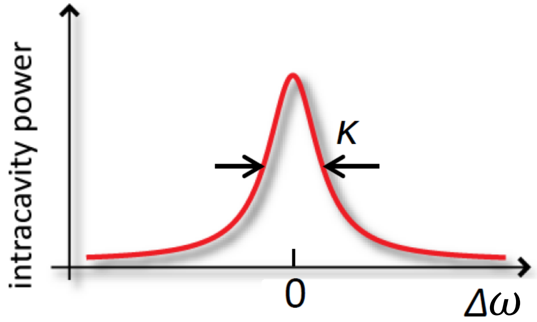
(makes sense, FT of exponential is a Lorentzian)

$$\frac{1}{Q_L} = \frac{1}{Q_{UL}} + \frac{1}{Q_e}$$

You measure the loaded Q, you can potentially calculate the unloaded (intrinsic) Q

Haus, "Waves and Fields in Optoelectronics", 1984, Prentice-Hall; Verhagen, "Microcavities", UvA 2020

Q Factor Units!



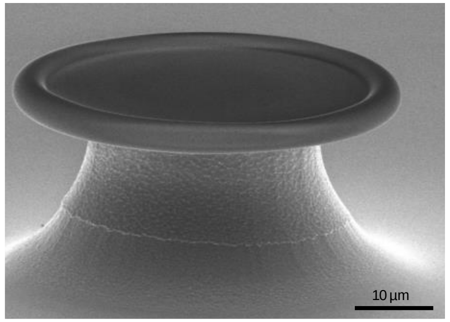
$$|\bar{Y}|^2 = \frac{\frac{1}{\tau_e}}{(\omega - \omega_e)^2 + \left(\frac{1}{2\tau_0} + \frac{1}{\tau_e}\right)^2} |\overline{s_+}|^2$$

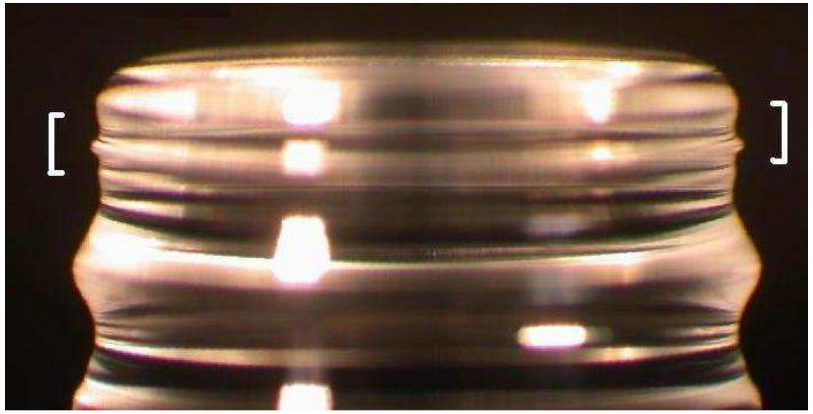
$$\frac{1}{\tau} = \frac{1}{2\tau_0} + \frac{1}{\tau_e}$$

As $\tau \downarrow; \frac{1}{\tau_e} \uparrow; \Delta\omega \uparrow; Q \downarrow$

$$Q = \tau\omega = \frac{2\pi c}{\lambda}\tau$$

$$Q = \frac{\lambda}{\Delta\lambda} \approx \frac{\omega}{\Delta\omega}$$





CaF$_2$, Q~10^{11}, 5 mm diameter

Maleki and co-workers, *PRL*, *102*(4), 043902.

Q=10^8→~10 fm, ~1 MHz, ~1x10^{-5} cm^{-1} , 1 neV, etc.

τ → ~100 ns

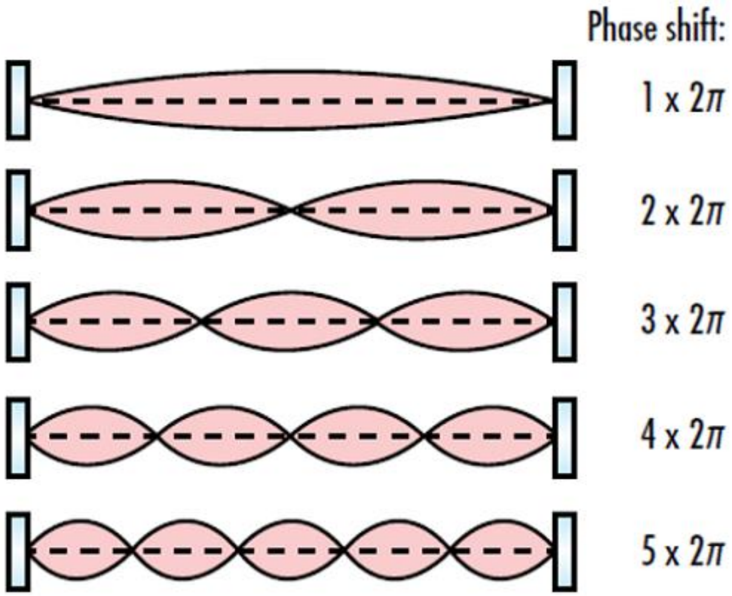
Haus, “Waves and Fields in Optoelectronics”, 1984, Prentice-Hall; Verhagen, “Microcavities”, UvA 2020

Free Spectral Range (better than Free Range?)

$$\vec{E} = \sum_{mode\#'s} A(x,y,z)\boxed{T(t)}$$

$$\Delta\omega_{FSR} = \omega_m - \omega_{m-1} = \frac{\pi c}{L}$$

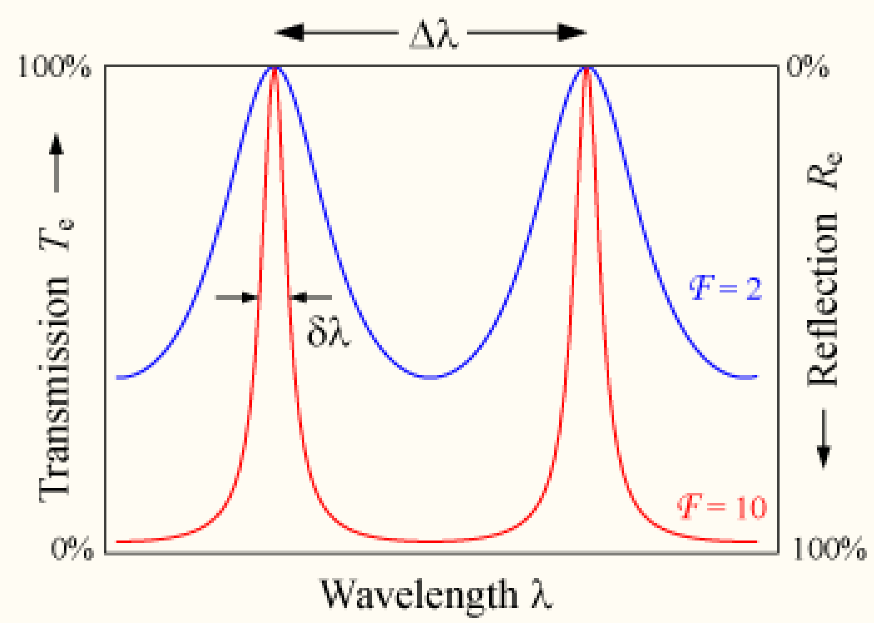
$$\Delta\lambda_{FSR} = \lambda_m - \lambda_{m-1} = \frac{\lambda_m^2}{2L}$$



mλ/2=L

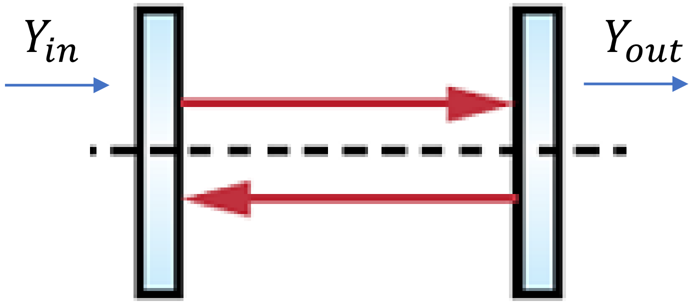
The smaller the L,
the larger the FSR

L↓; FSR↑



That cavity's got Finesse!

Length=L; Refractive index= n



Reflectivity = R_1 R_2; T_2

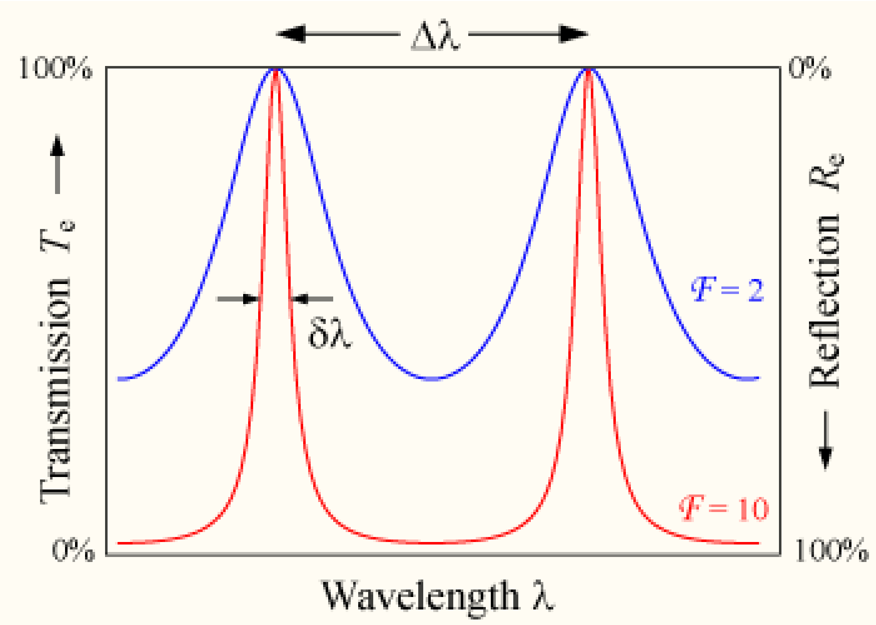
Transmission = 1-R_1 =T_1

Change in Electric Field (T) during one round trip: $g(\omega) = \sqrt{R_1R_2}e^{-2i\omega Ln/c}$

After multiple trips: $Y_{out} = Y_{in}\sqrt{T_1T_2}e^{-i\omega Ln/c}(1 + g(\omega) + g(\omega)^2 + \cdots)$

$$Y_{out} = \frac{Y_{in}\sqrt{T_1T_2}e^{-i\omega Ln/c}}{1 - g(\omega)}$$

$$|Y_{out}|^2 = \frac{|Y_{in}|^2T_1T_2}{1 + R_1R_2 - 2\sqrt{R_1R_2}\cos(\frac{2L\omega n}{c})}$$



$$\Delta\omega_{FWHM} = \frac{\left(1 - \sqrt{R_1R_2}\right)c}{(R_1R_2)^{1/4}nL} = \frac{\pi c}{FnL} = \frac{FSR}{F}$$

$$F = \frac{\pi(R_1R_2)^{1/4}}{1 - \sqrt{R_1R_2}} \qquad \Delta\omega_{FSR} = \frac{\pi c}{nL}$$

As F↑; $\Delta\omega$ ↓

Haus, "Waves and Fields in Optoelectronics", 1984, Prentice-Hall; Verhagen, "Microcavities", UvA 2020

Q vs F!

$$F = 2\pi \times \#round\ trips\ before\ decay\ to\ 1/e \times |Y|^2$$

$$F = 2\pi \times \frac{stored\ energy}{energy\ loss\ per\ round\ trip}$$

$$F = \frac{\pi (R_1 R_2)^{1/4}}{1 - \sqrt{R_1 R_2}}$$

No L dependence!

Purely a function
of the cavity losses

Depends on L!

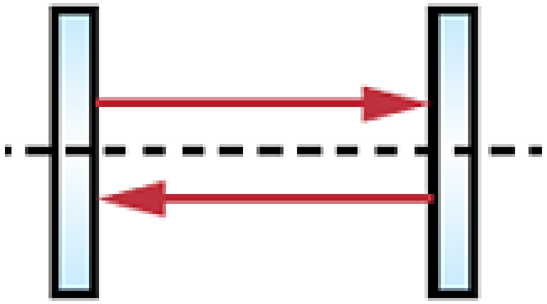
$$Q = 2\pi \times \#optical\ cycles\ before\ decay\ to\ 1/e \times |Y|^2$$

$$Q = 2\pi \times \frac{stored\ energy}{energy\ loss\ per\ cycle}$$

$$Q = \frac{2\pi c}{\lambda}\tau \qquad Q = \frac{\lambda}{\Delta\lambda}$$

Depends on L! and

Purely a function
of cavity lifetime
and linewidth



As R↑;F↑;Q↑

As L↑;F – ;Q↑

$$Q = \frac{\omega}{\Delta\omega_{FSR}} F$$

As F↑;Q↑, photons are localized in TIME and FREQUENCY

Saleh and Teich, “Fundamentals of Photonics”, 1991, Wiley; Smith and co-workers, Nanotechnology, 27, 274003, 2016
Haus, “Waves and Fields in Optoelectronics”, 1984, Prentice-Hall; Verhagen, “Microcavities”, UvA 2020

Mode Volume

“…where V is the volume of the resonator”

Physical volume? What about loss?

$$V = \frac{\int dV |E|^2}{\max(|E|^2)}$$

Normalized. Prone to artifacts (particularly for very low V).

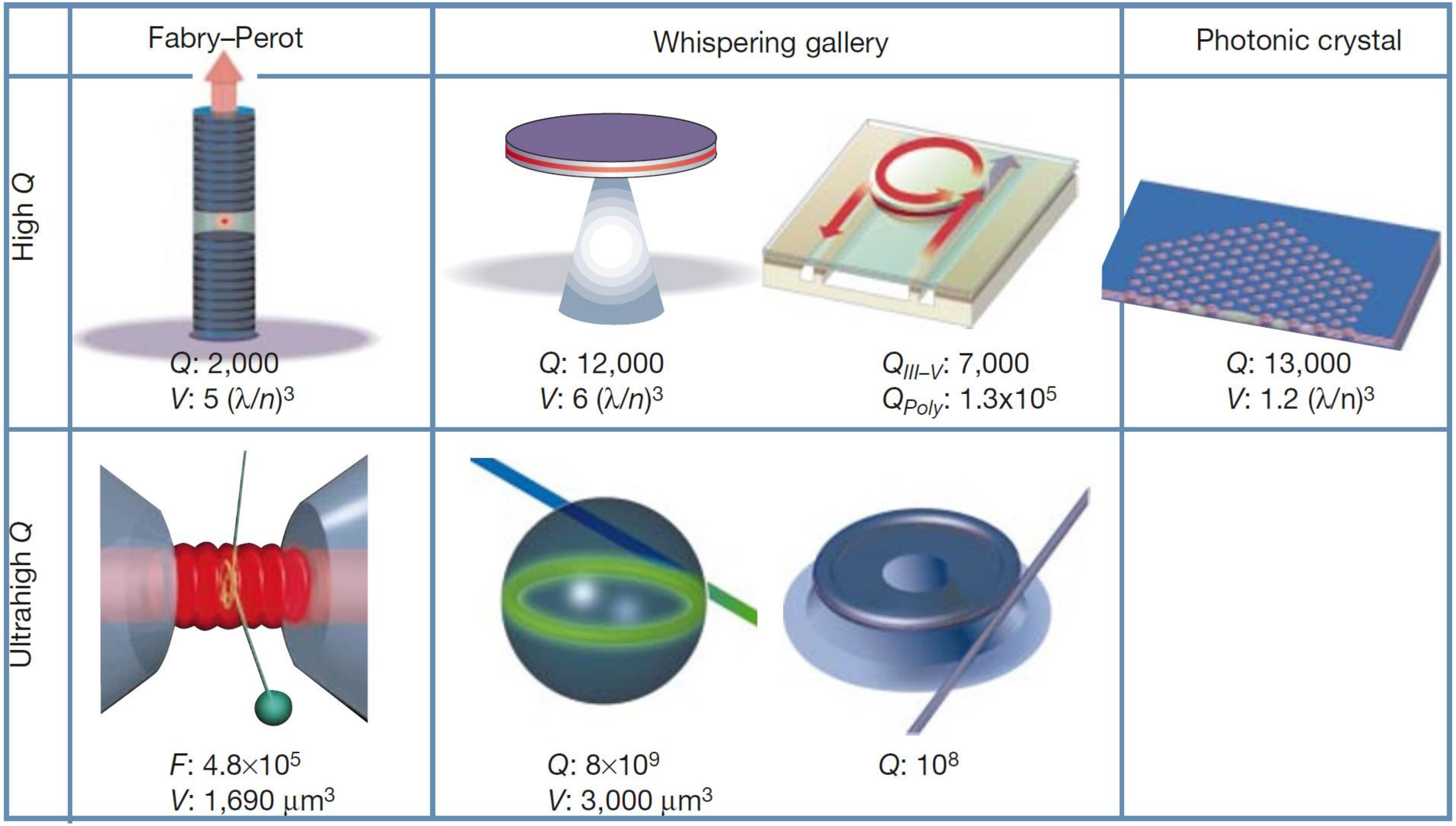
Many other definitions. Lumerical even offers multiple options.

As $V\downarrow$, photons are localized in SPACE

Hard to get smaller than λ^3 for dielectric microcavity

Purcell, Phys. Rev. 69, 681, 1946

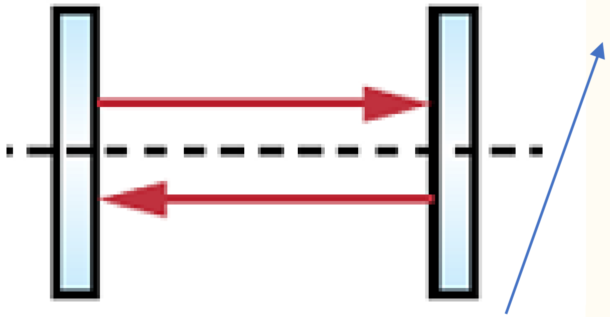
Microcavity Menagerie



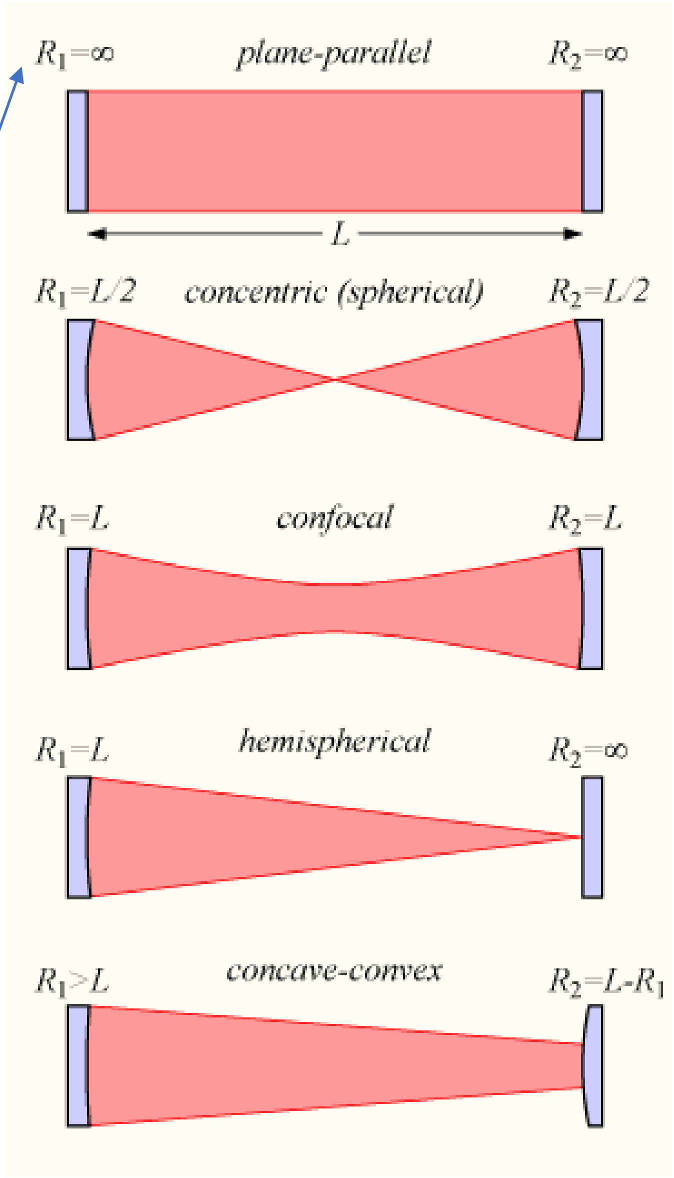
	Fabry–Perot	Whispering gallery		Photonic crystal
High Q	Q: 2,000 V: 5 $(\lambda/n)^3$	Q: 12,000 V: 6 $(\lambda/n)^3$	$Q_{III–V}$: 7,000 Q_{Poly}: $1.3\text{x}10^5$	Q: 13,000 V: 1.2 $(\lambda/\text{n})^3$
Ultrahigh Q	F: 4.8×10^5 V: 1,690 μm^3	Q: 8×10^9 V: 3,000 μm^3	Q: 10^8	

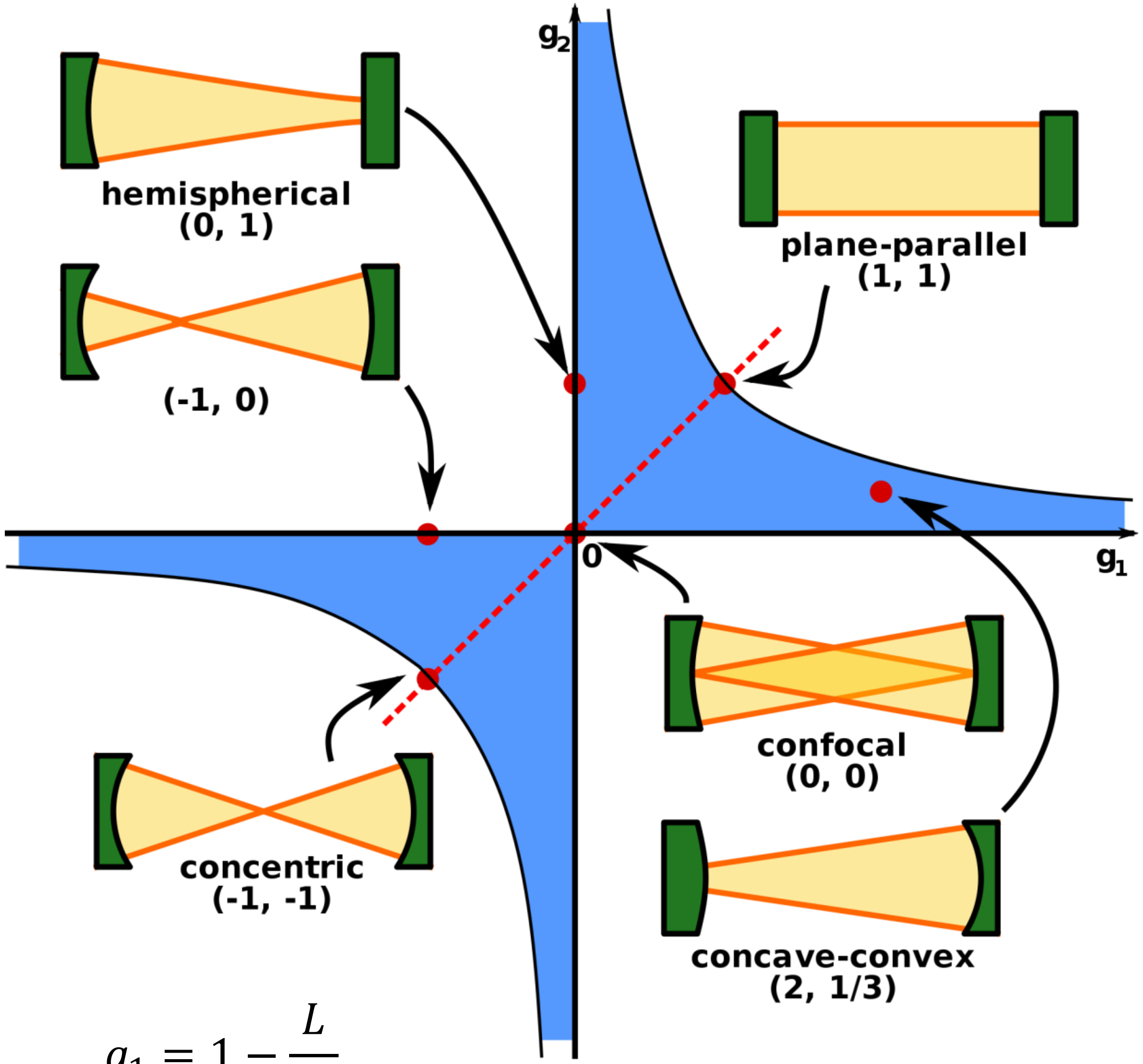
Vahala, Nature, 424, 83, 2003

Fun with Fabry Perot Cavities…



Radius of Curvature



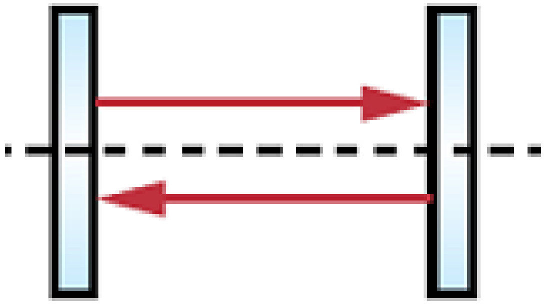


$$g_1 = 1 - \frac{L}{R_1}$$

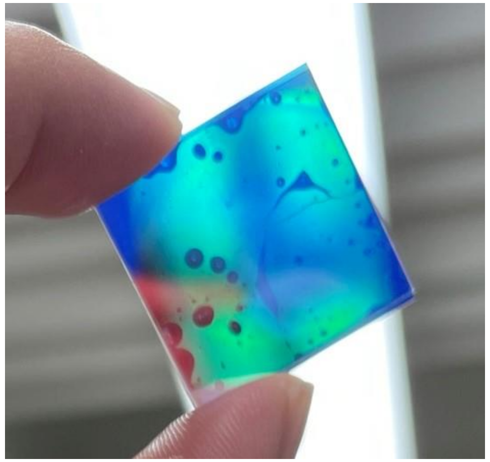
$$g_2 = 1 - \frac{L}{R_2}$$

https://en.wikipedia.org/wiki/Optical_cavity

Planar Fabry Perot Microcavities (are everywhere…)



Planar cavity
by Tzu-Ling in my group



Easy to make!

Low Q (10-300ish)

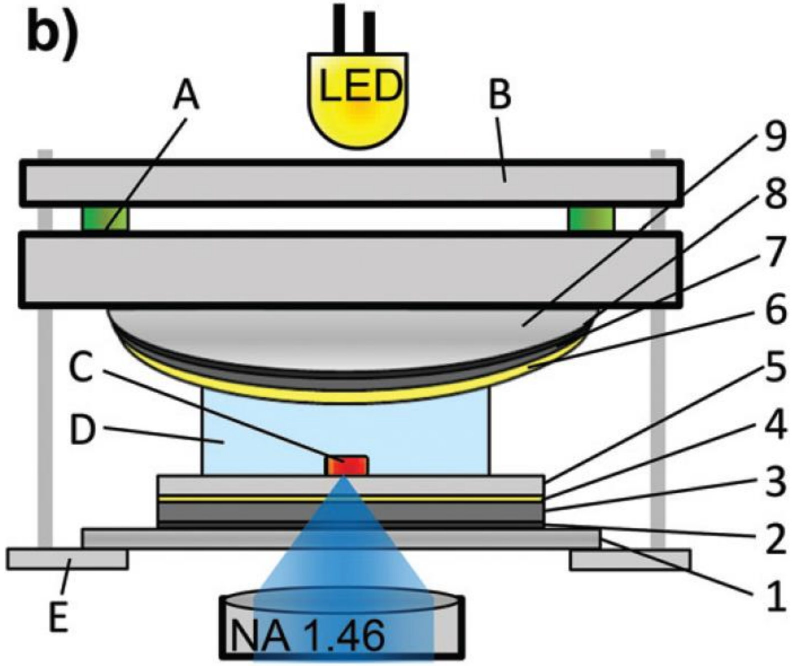
No well-defined mode volume, must make use of quasi-normal modes*

$$V_m = \frac{\pi L^2 \lambda}{1 - R}$$

Modes along "columns"

Not obviously tunable (ie, L is set)

Can deform cavity
Can change k vector!

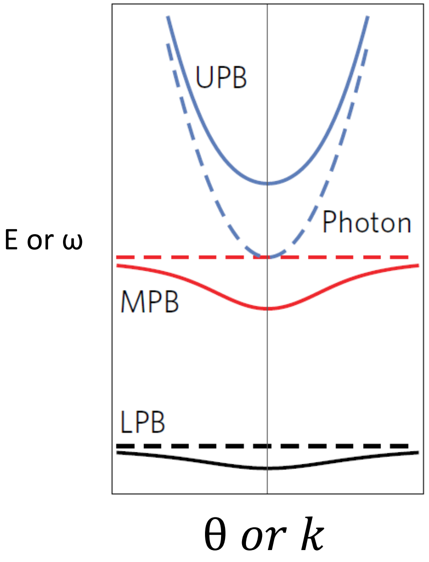


Konrad, Meixner and co-workers, *Nanoscale* **2015**, 7, 10204.

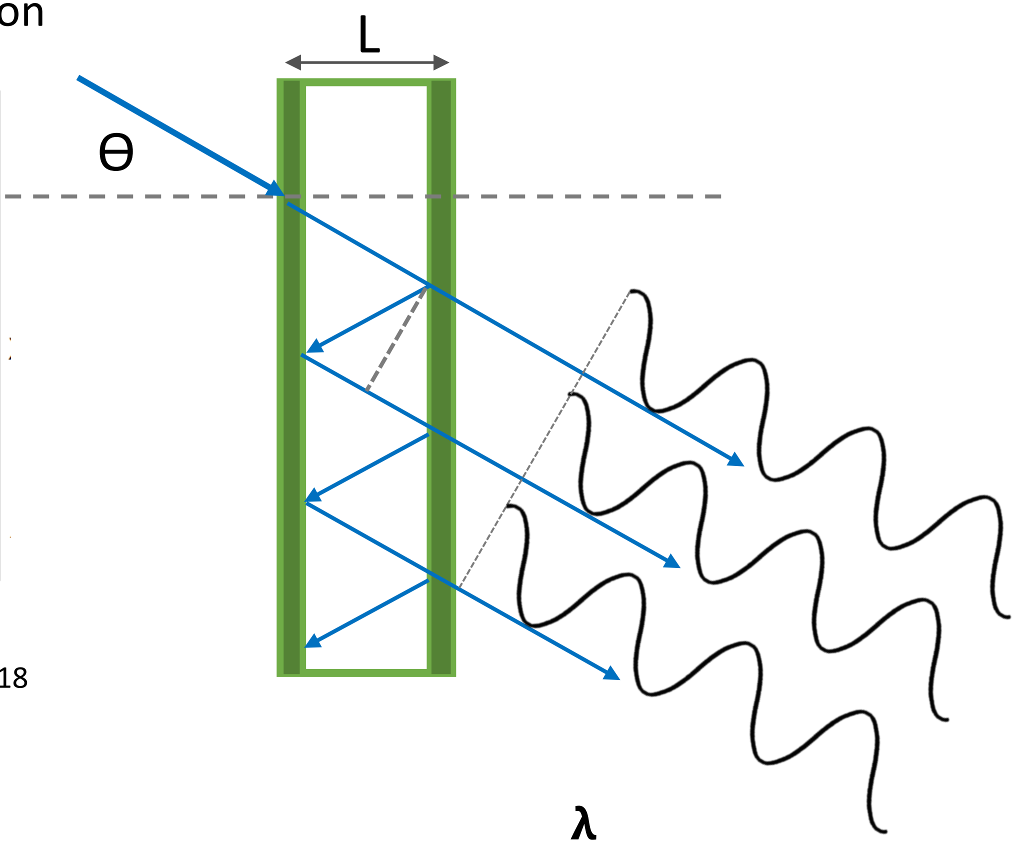
*Ujihara, K. *Jpn. J. Appl. Phys.* **1991**, L901.

Planar Fabry Perot Cavities (are sort of tunable)

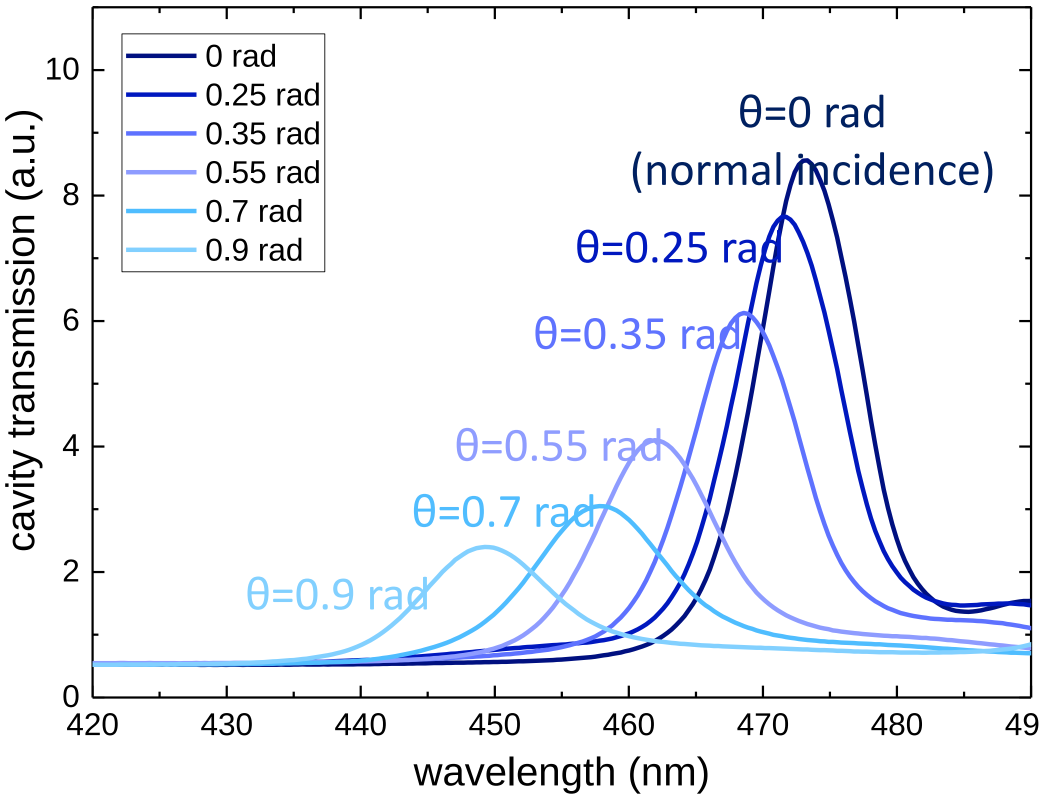
Parabolic dispersion

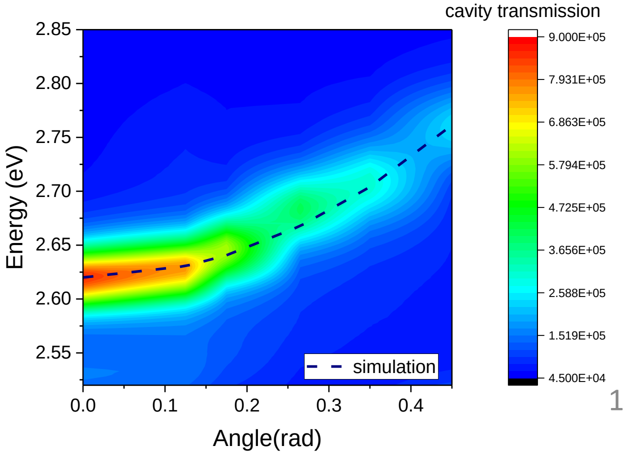


Nature Physics, 14, 130, 2018



$$\delta L = 2Ln\ \cos\theta = \frac{\boldsymbol{\lambda}}{2}N$$





https://byjus.com/jee/thin-film-interference/; Dr. Tzu-Ling Chen, Goldsmith group

Spatial Modes

$$\vec{E} = \sum_{mode\#'s} \boxed{A(x,y,z)}\, Y(t)$$

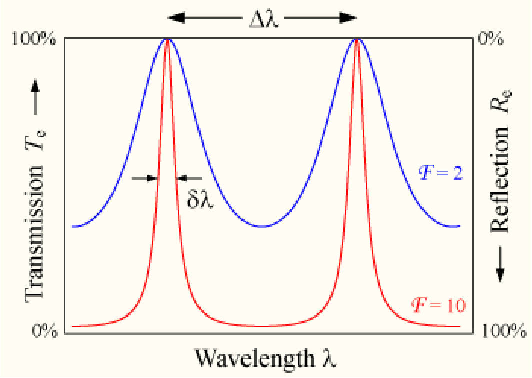
Laguerre-Gaussian modes (cylindrical symmetry)

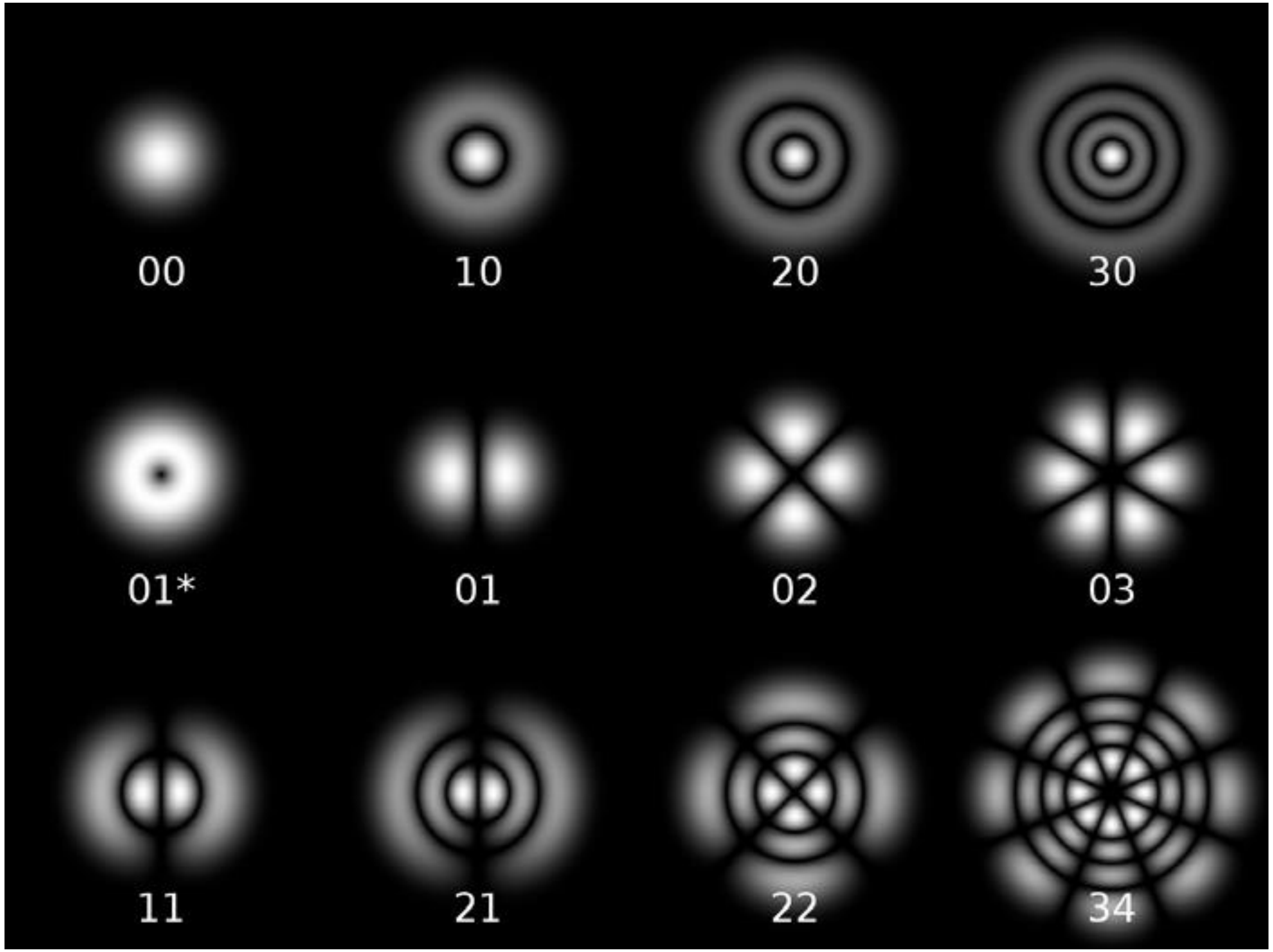
“Transverse Electromagnetic” mode, or TEM$_{p\ell}$

TEM$_{00}$

In general, different spatial modes have different energies (Confocal is special, mode spectrum converges)

In an ideal, 1D FP, Transmission can be 100%. But with loss and imperfect mode matching, max % transmission can vary.





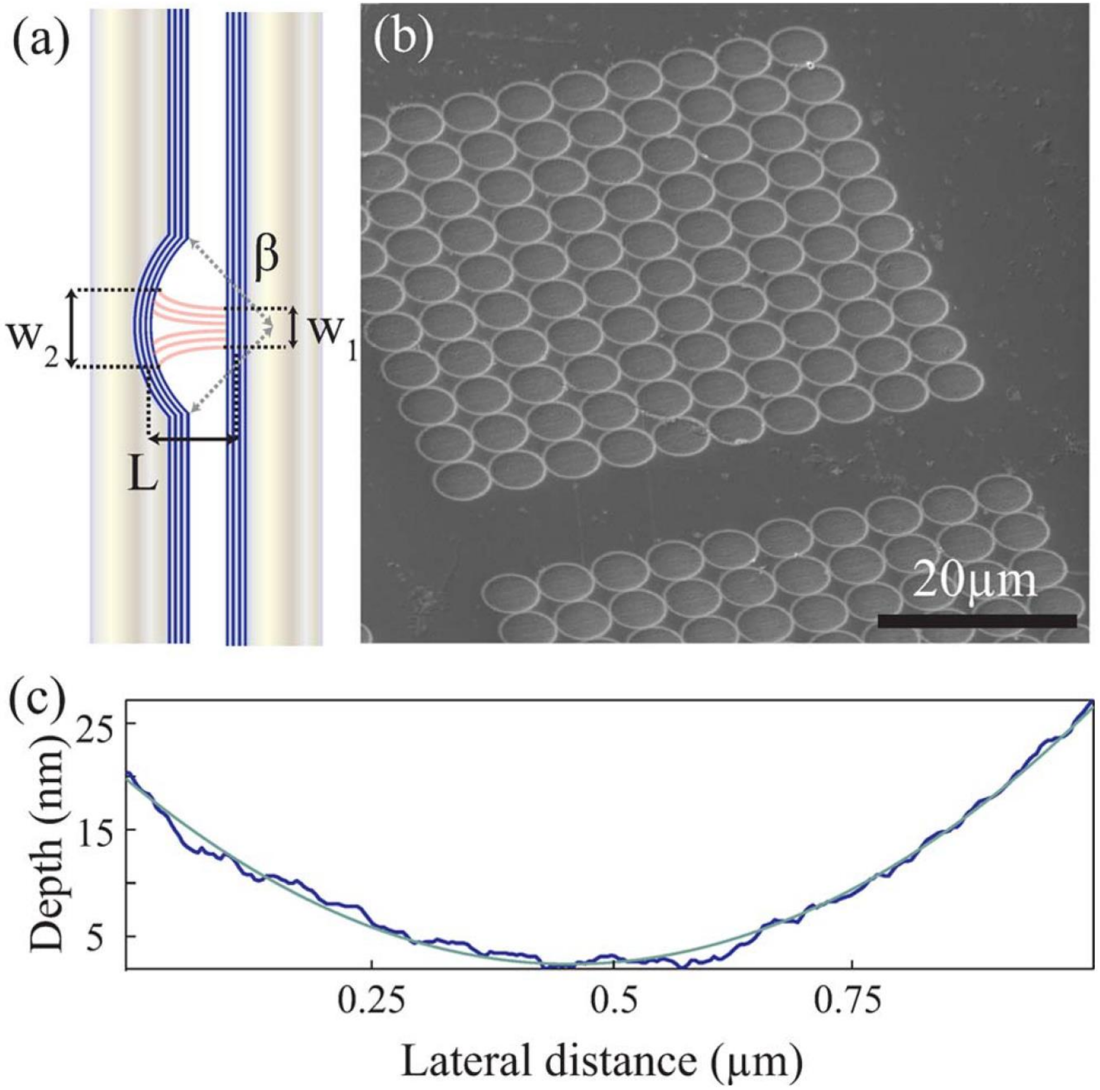
Yariv, A. 1991, Optical Electronics, Saunders College Publishing, 4th ed.

Fabry Perot Microcavities, Part 1

Developed by Jason Smith @Oxford (other early work from Warburton, Reichel, Sandoghdar)

Generally made by Focused Ion Beam (FIB) milling

Then depo$it high reflectivity optical coating$



Smith and co-workers, Optics Letters, 35, 2010, 2010

Smith and co-workers, Nanotechnology, 27, 274003, 2016

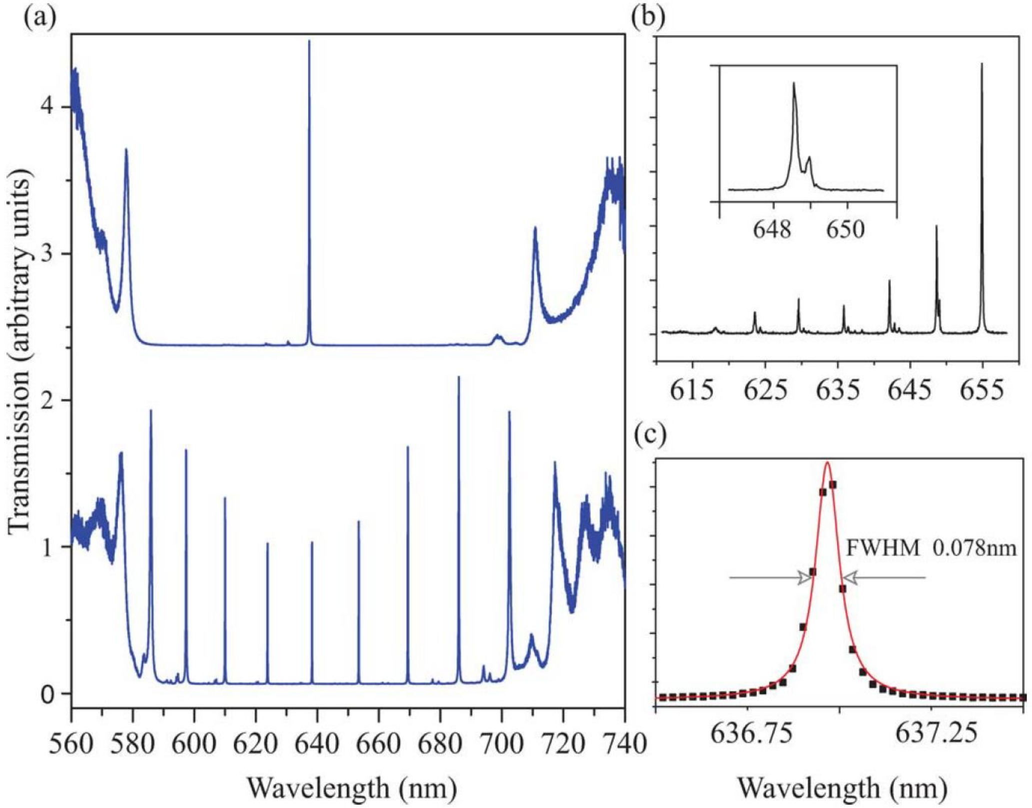
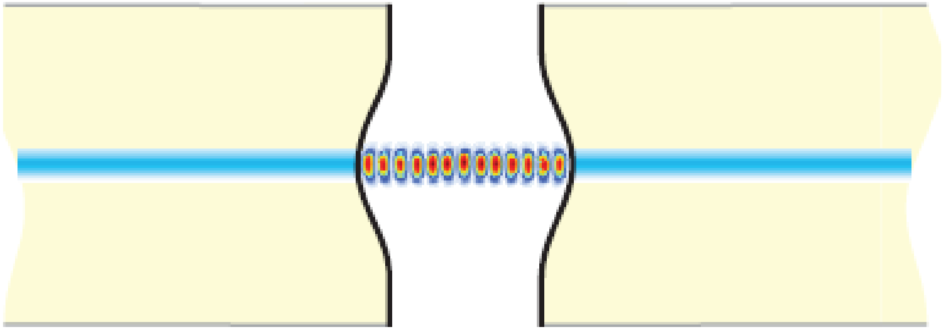
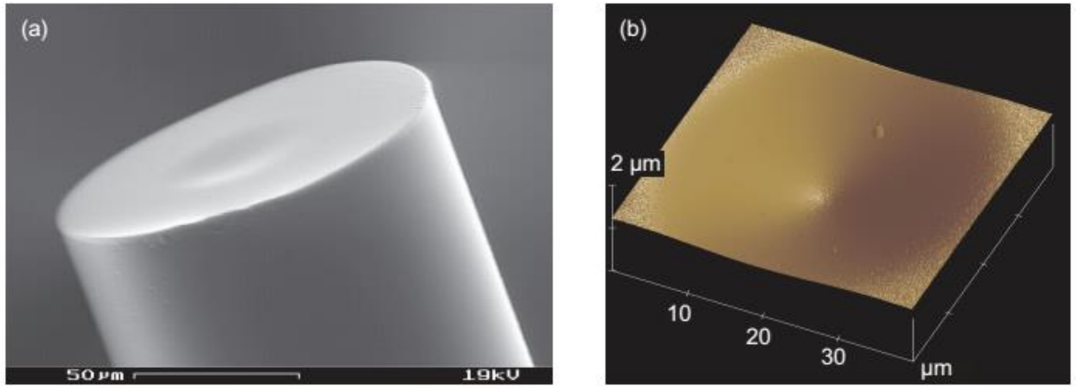
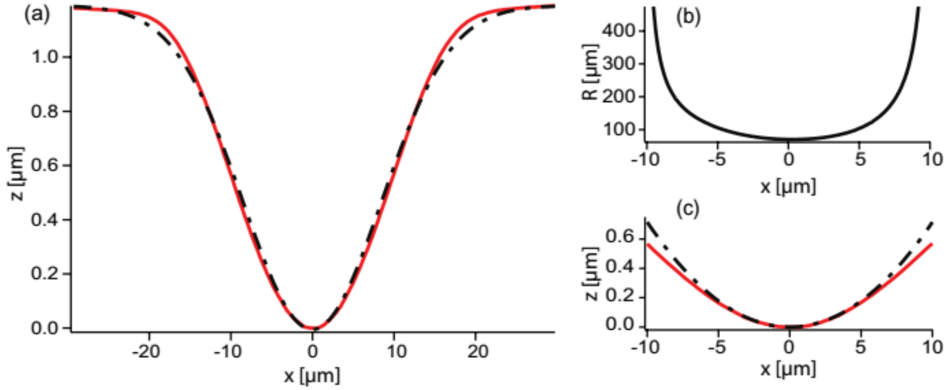


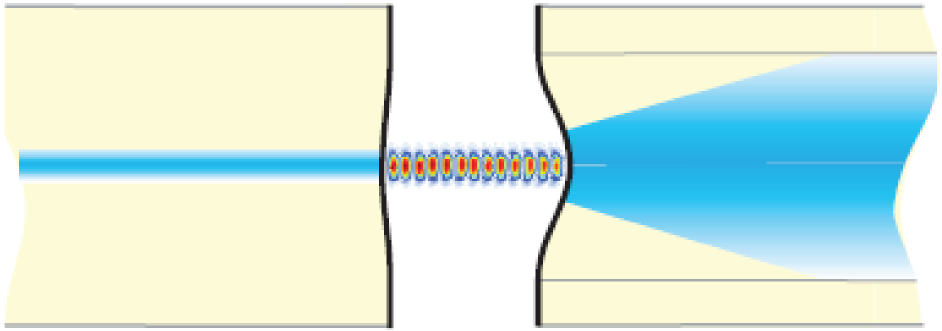
Fig. 2. (Color online) White-light transmission spectra of the cavities: (a) cavity A at $L = 3.0\ \mu$m and $L = 12.3\ \mu$m; (b) HG modes from a single longitudinal mode with (1,0) (0,1) splitting (inset); (c) a high-Q longitudinal resonance (scatter) with Lorentzian curve fit (solid curve).

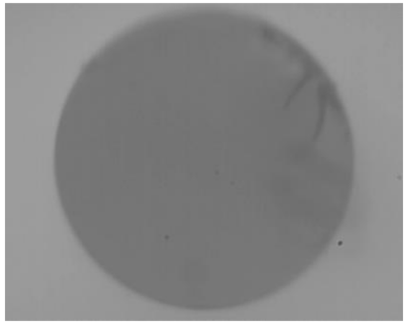
Fabry Perot Microcavities, Part 2, Fiber based!











Developed by David Hunger (now at KIT) with Jakob Reichel@ Sorbonne

Use a CO_2 laser to smoothly ablate the surface

Already integrated into photonic infrastructure

Hunger, Hansch, Reichel, coworkers, *NJP* **12**, 065038 (2010); *AIP Adv* **2**, 02119 (2012)

Fiber Fabry-Perot Microcavities in the Goldsmith Lab

Research Article Vol. 29, No. 2 / 18 January 2021 / *Optics Express* 974

Optics EXPRESS

Tunable fiber Fabry-Perot cavities with high passive stability

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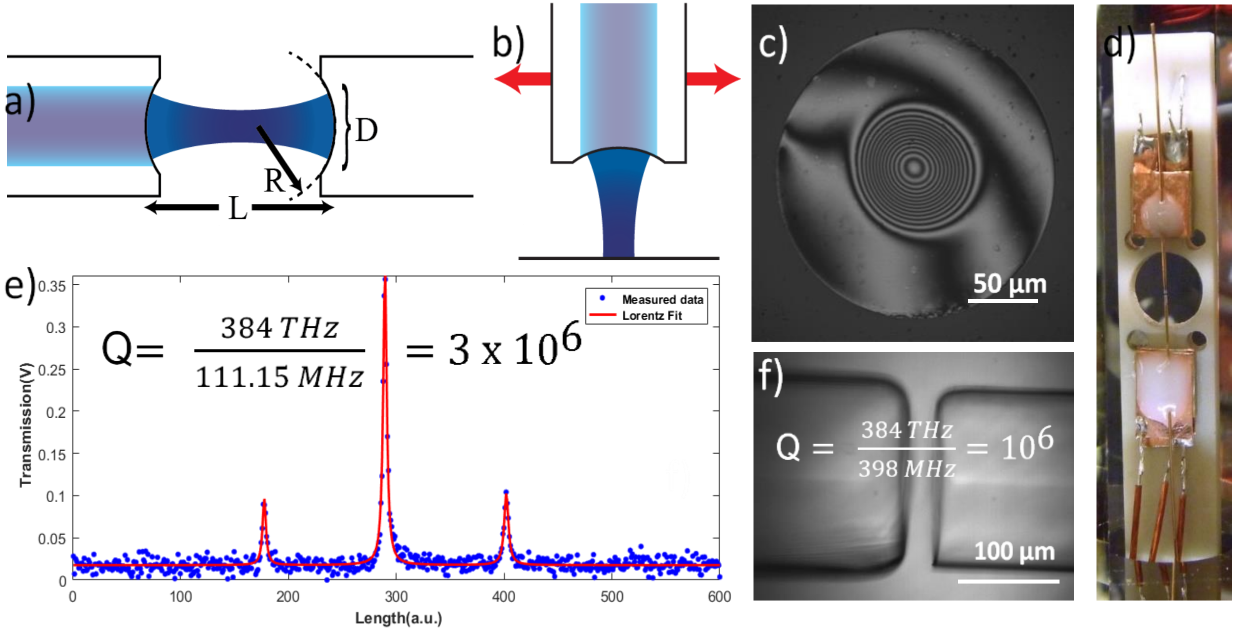
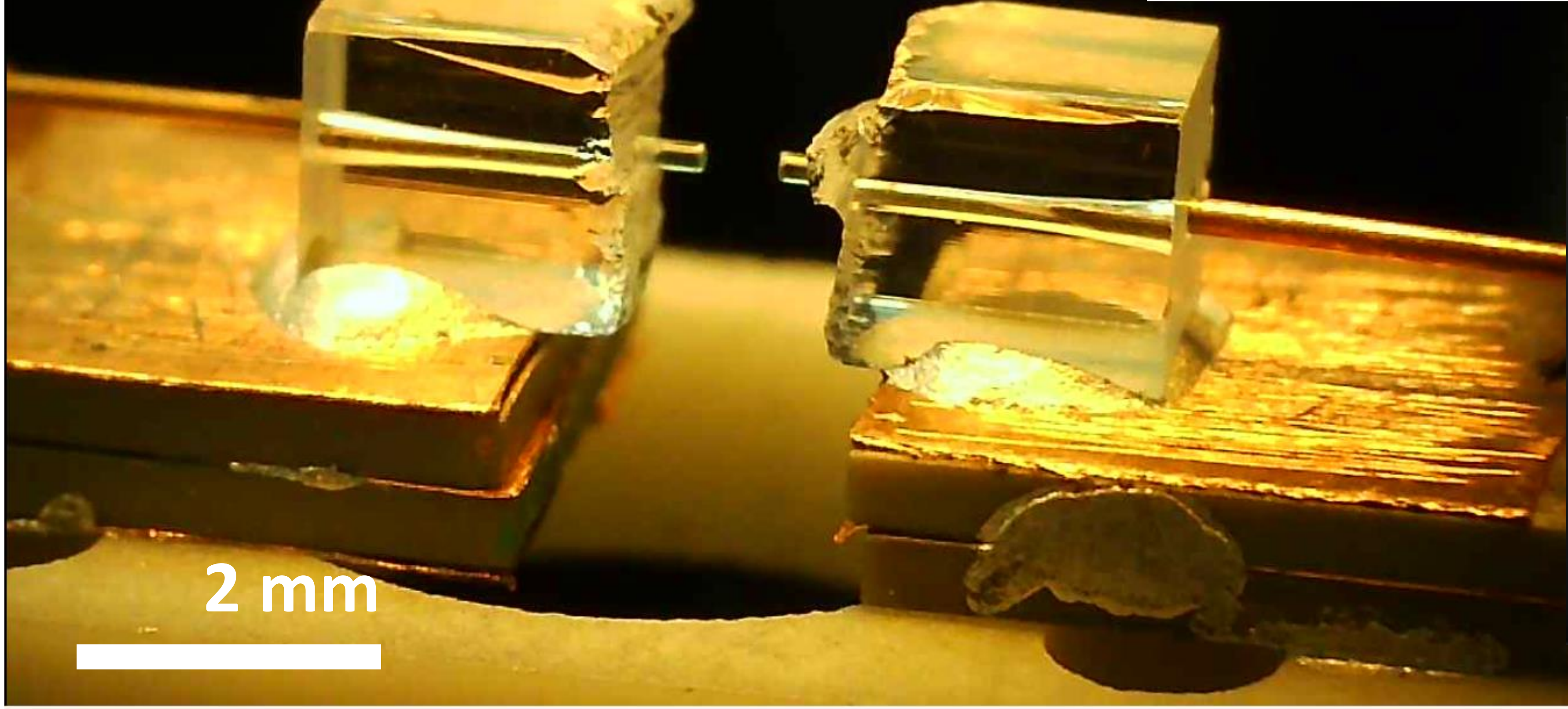
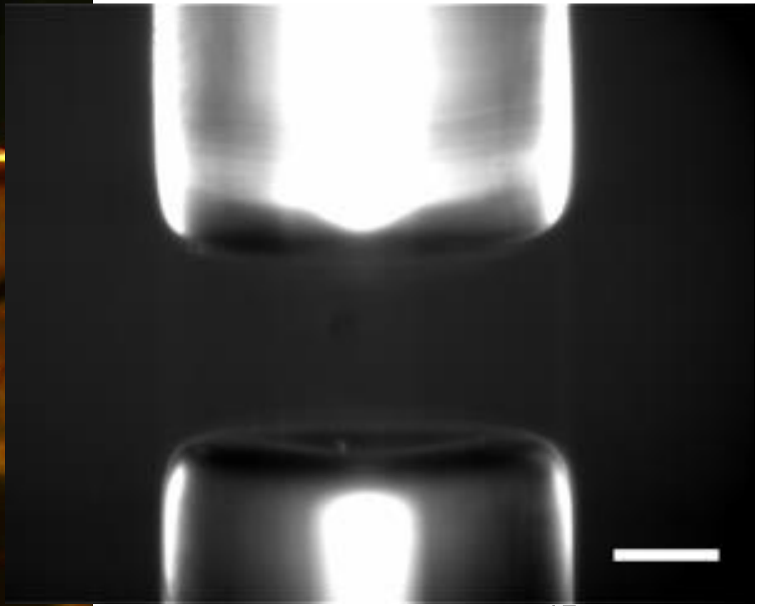
[3] *carlos.salazar@iap.uni-bonn.de*
[4] *d.pandey@iap.uni-bonn.de*
http://quantum-technologies.iap.uni-bonn.de/

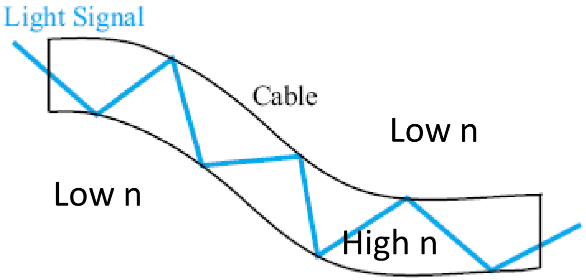


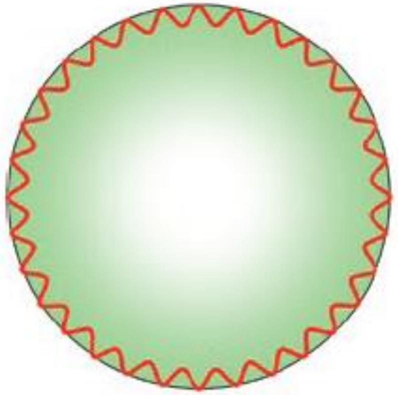




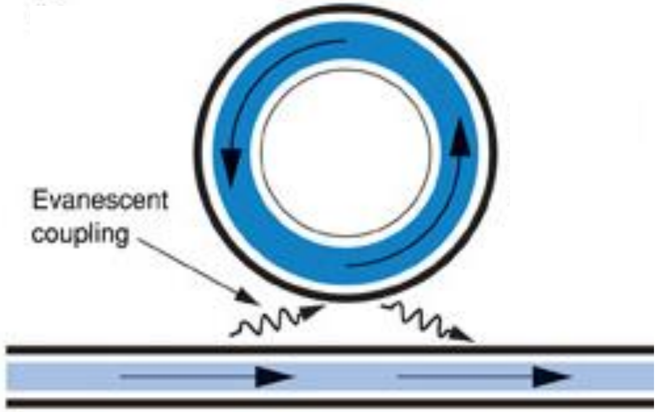
Whispering Gallery Mode Microresonators, Part 1

Total internal reflection

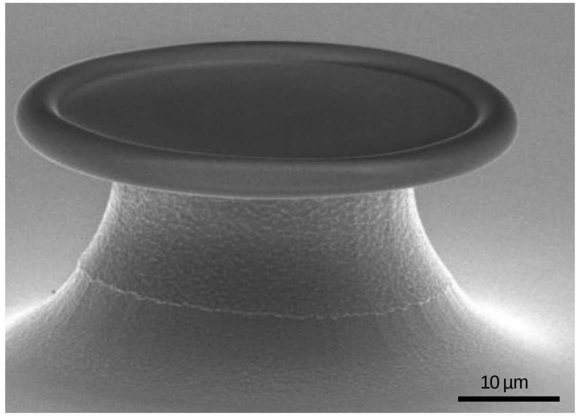




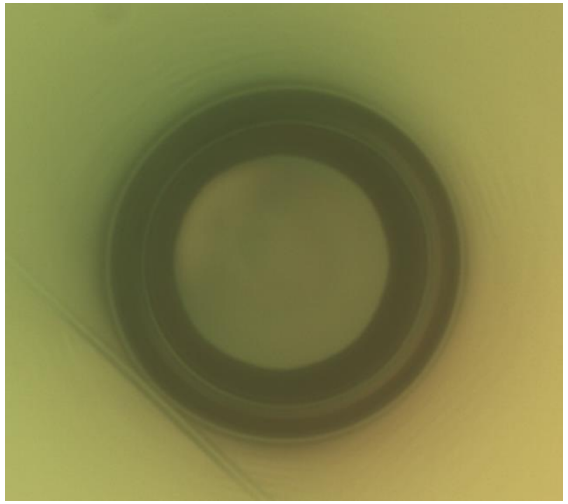
Whispering gallery modes of guided light



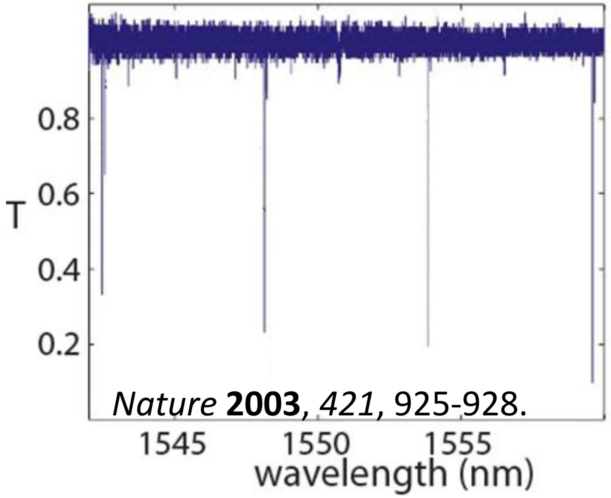
Only light of $\lambda = \dfrac{2\pi r n}{m}$ couples to cavity



Extremely smooth, and negligible loss! (Developed by Vahala, Caltech)

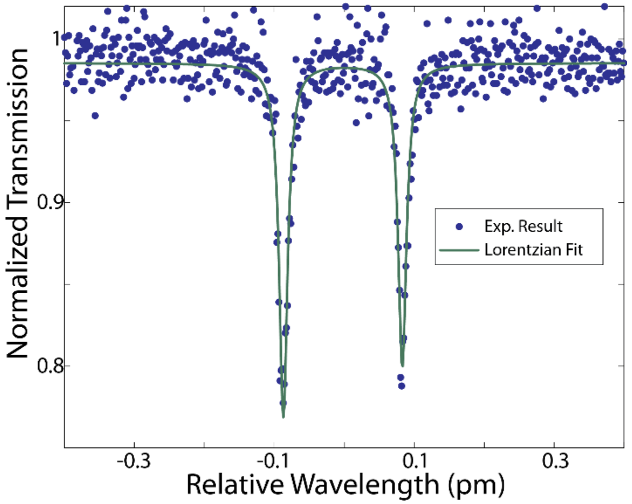


Couple evanescently to “leaky” fiber

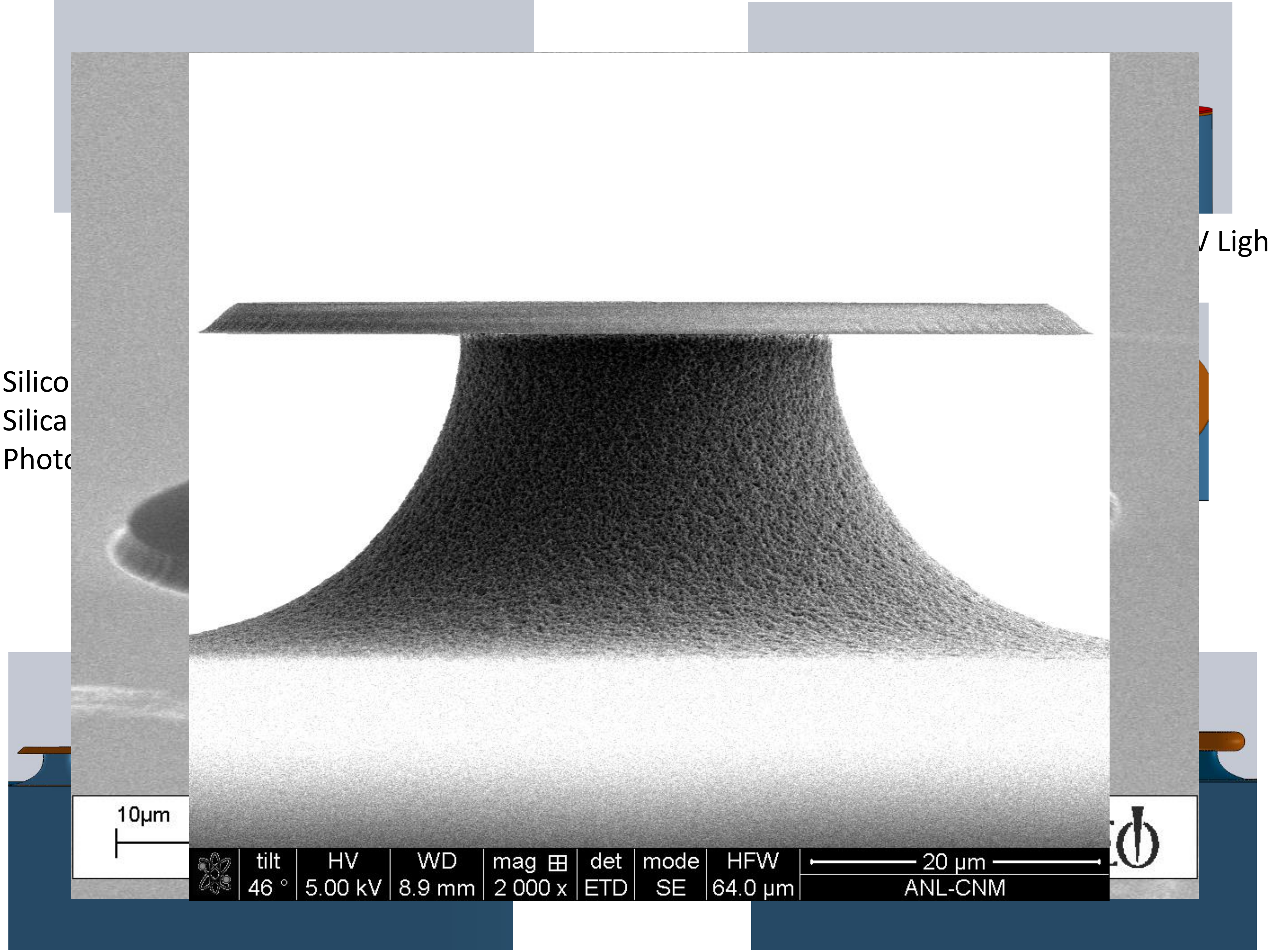


Nature **2003**, *421*, 925-928.

Dips in transmission spectra at resonance wavelengths



$Q = \dfrac{\lambda}{\Delta\lambda}$, 1 x 10^8; FWHM = 15fm

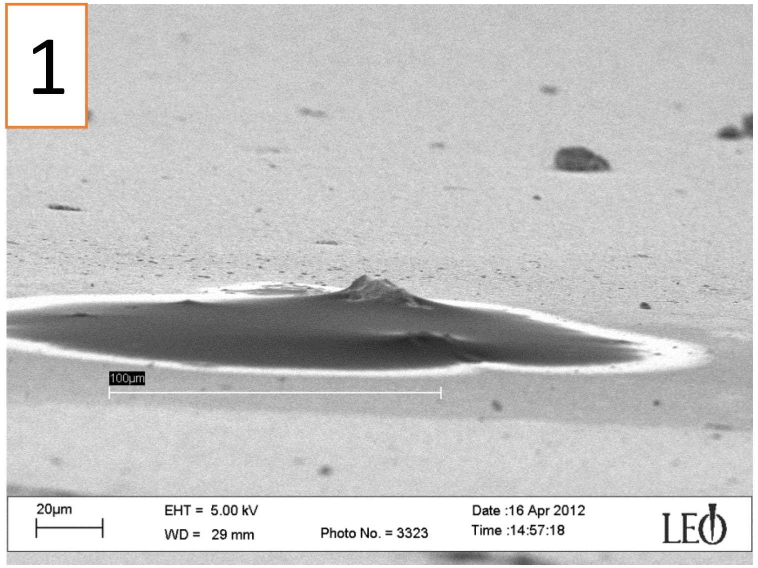


Silico
Silica
Photo

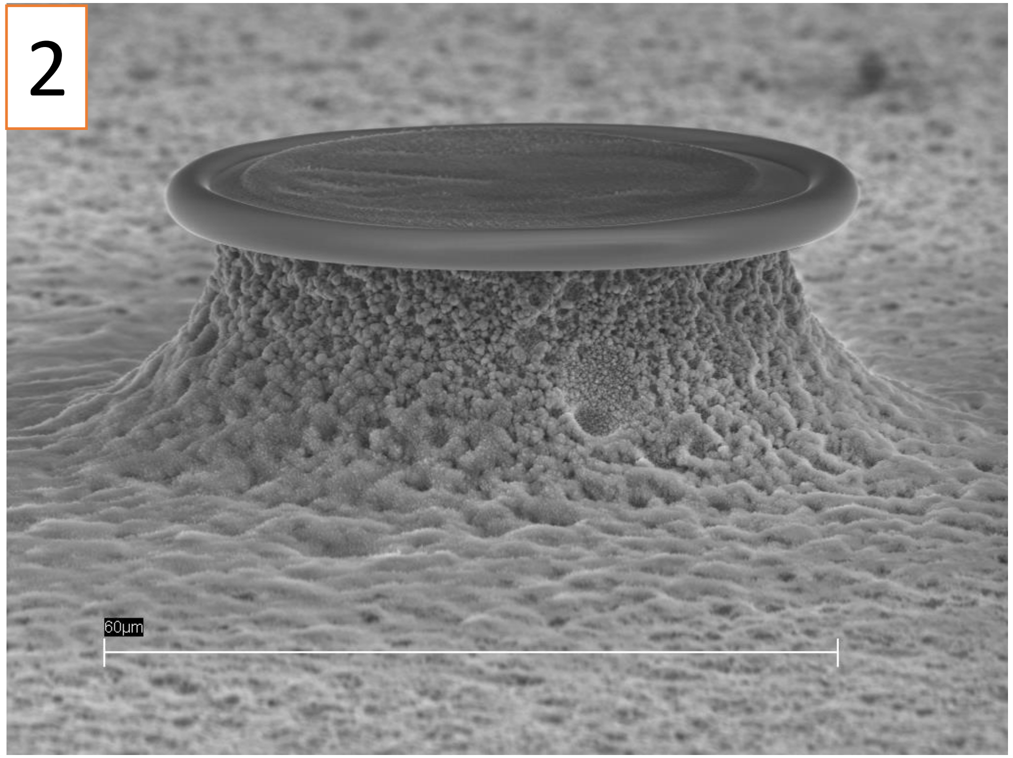
/ Light

How much power?

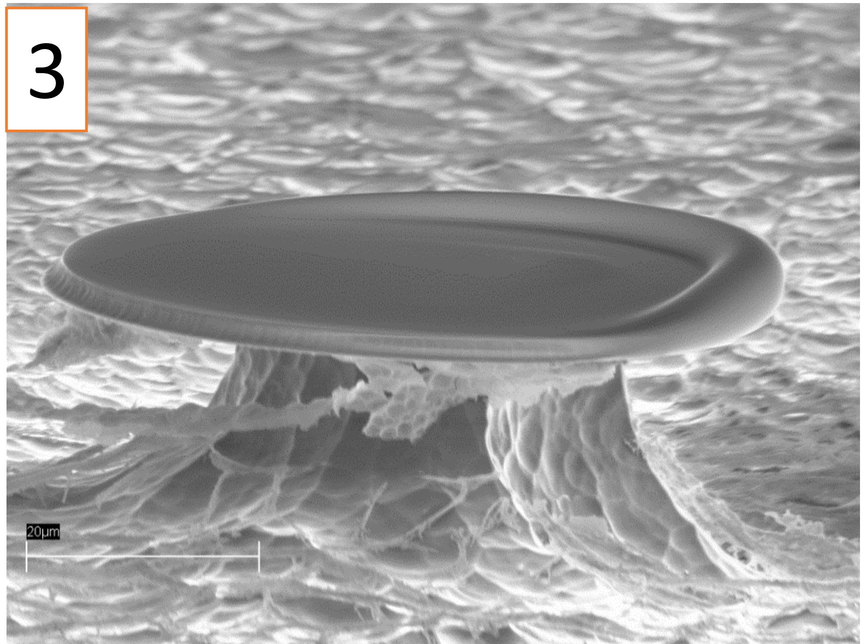
1



2

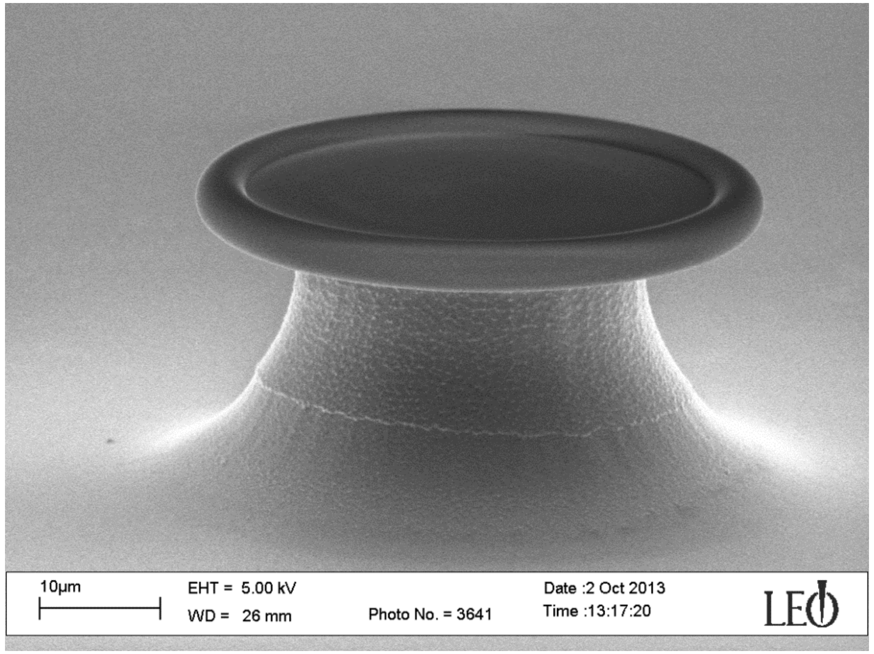


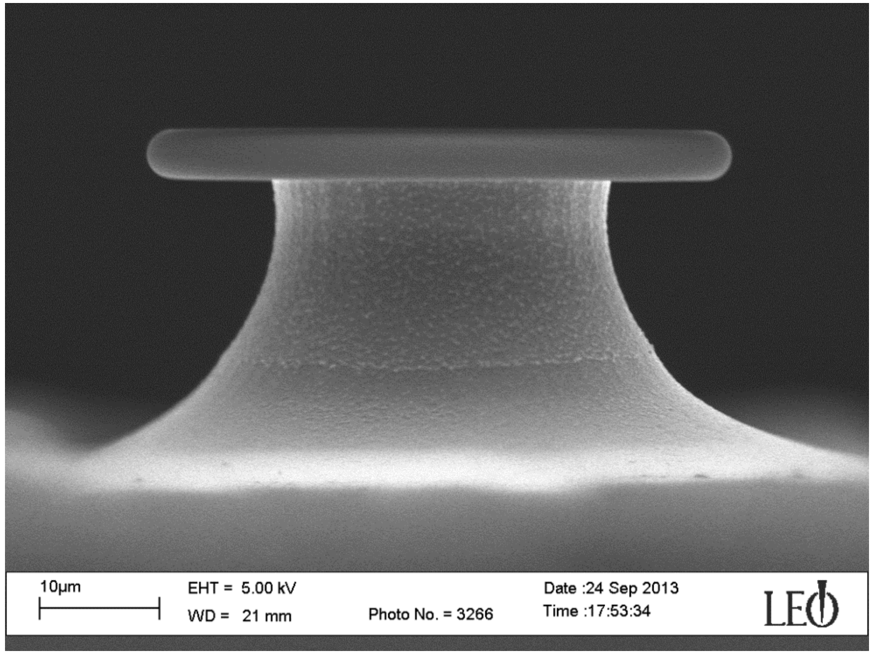
3

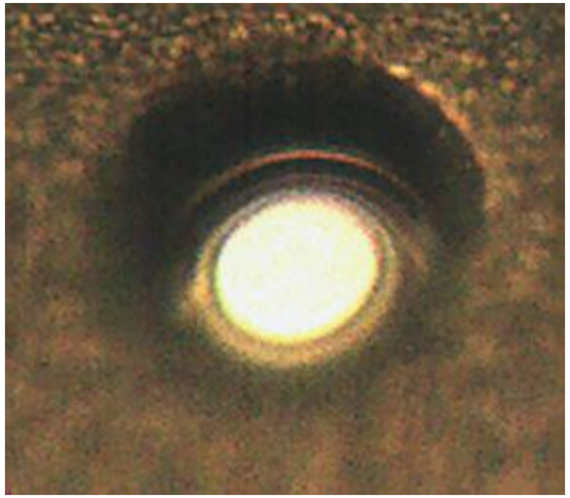


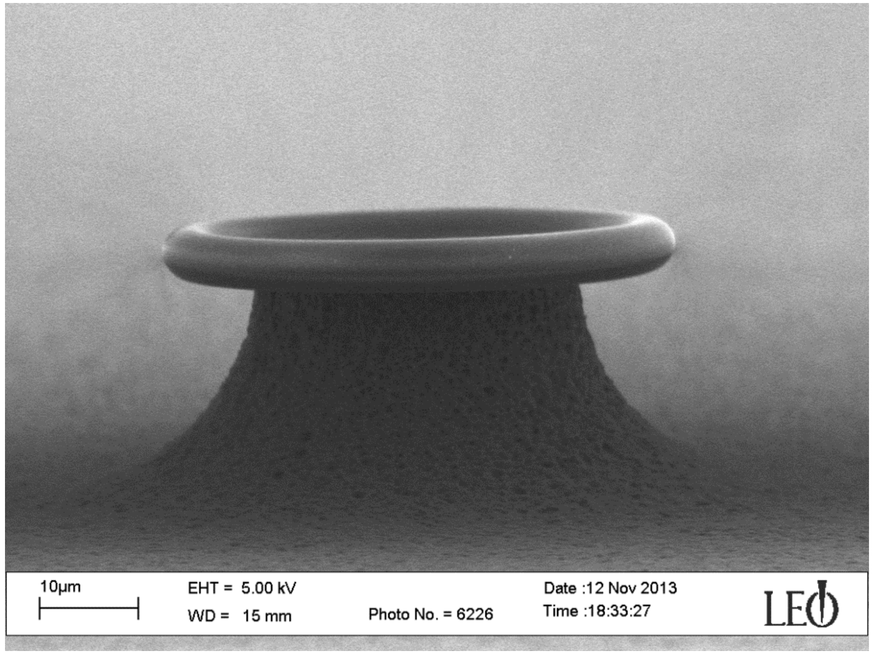
1. WAY too much power
2. Too much power
3. Not enough power

Just Right.

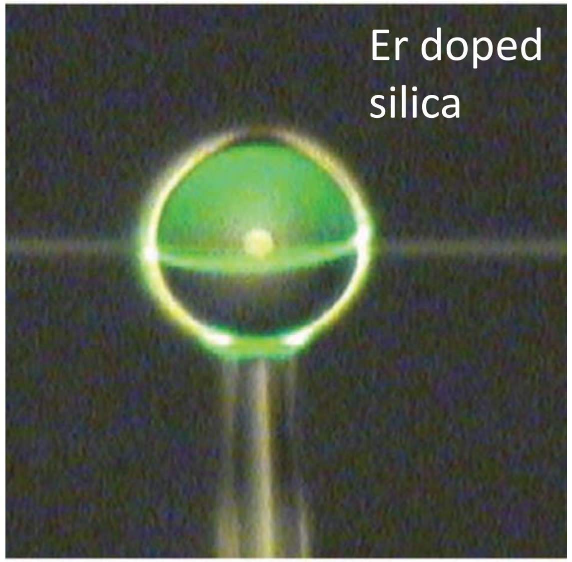

10µm
EHT = 5.00 kV
WD = 26 mm
Photo No. = 3641
Date :2 Oct 2013
Time :13:17:20
LEO


10µm
EHT = 5.00 kV
WD = 21 mm
Photo No. = 3266
Date :24 Sep 2013
Time :17:53:34
LEO



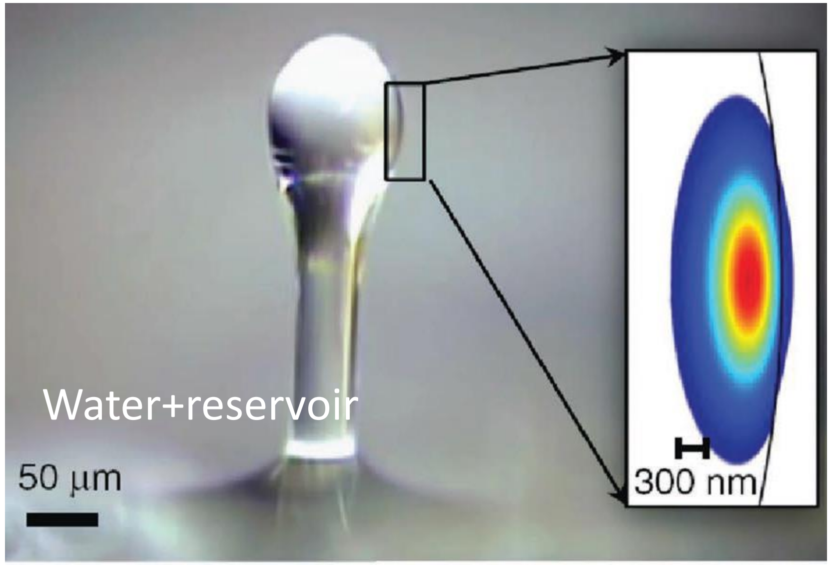

10µm
EHT = 5.00 kV
WD = 15 mm
Photo No. = 6226
Date :12 Nov 2013
Time :18:33:27
LEO

Whispering Gallery Mode Microresonators, Part 2

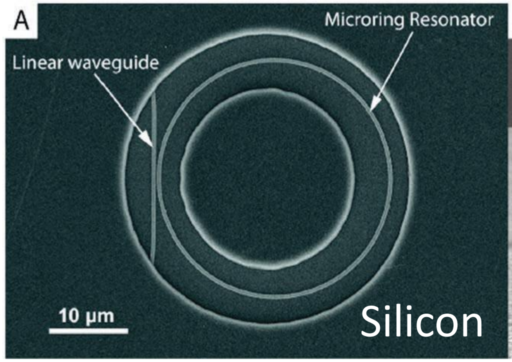


L. Yang, PhD Thesis, California Institute of Technology, Pasadena, CA, USA **2005**.

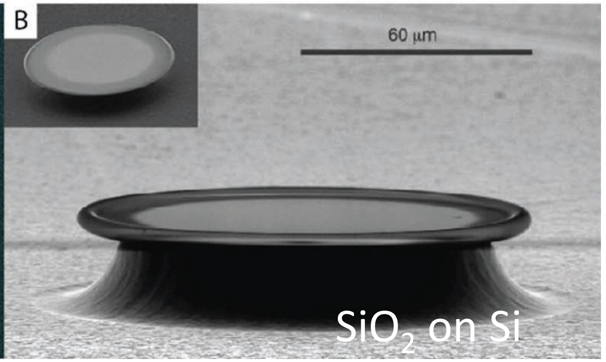
B. Way, R. K. Jain, M. Hossein-Zadeh, *Opt. Lett.* **2012**, *37*, 4389.



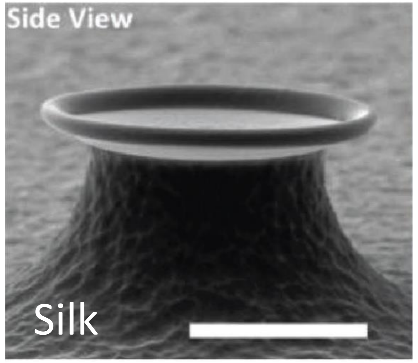
S. Maayani, L. L. Martin, T. Carmon, *Nat. Commun.* **2016**, *7*, 194101.



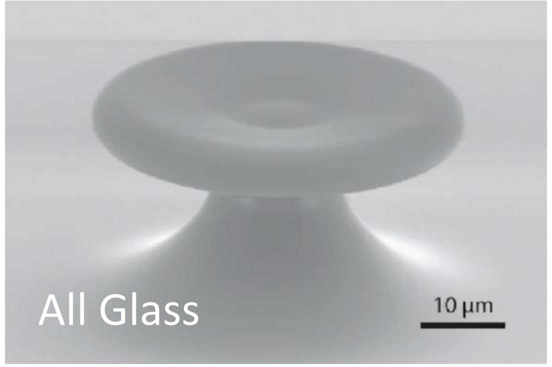
A. L. Washburn, L. C. Gunn, R. C. Bailey, *Anal. Chem.* **2009**, *81*, 9499.



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

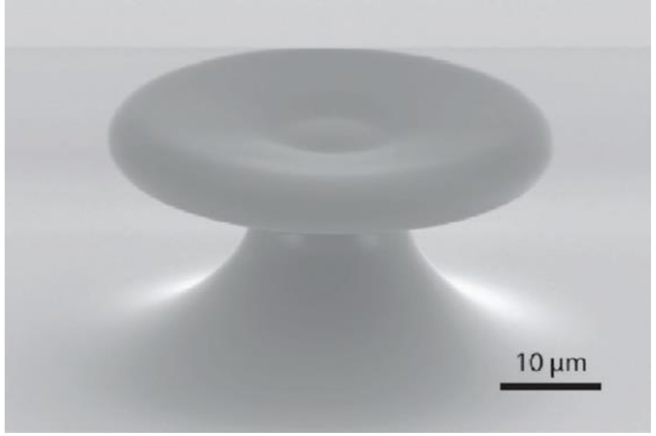


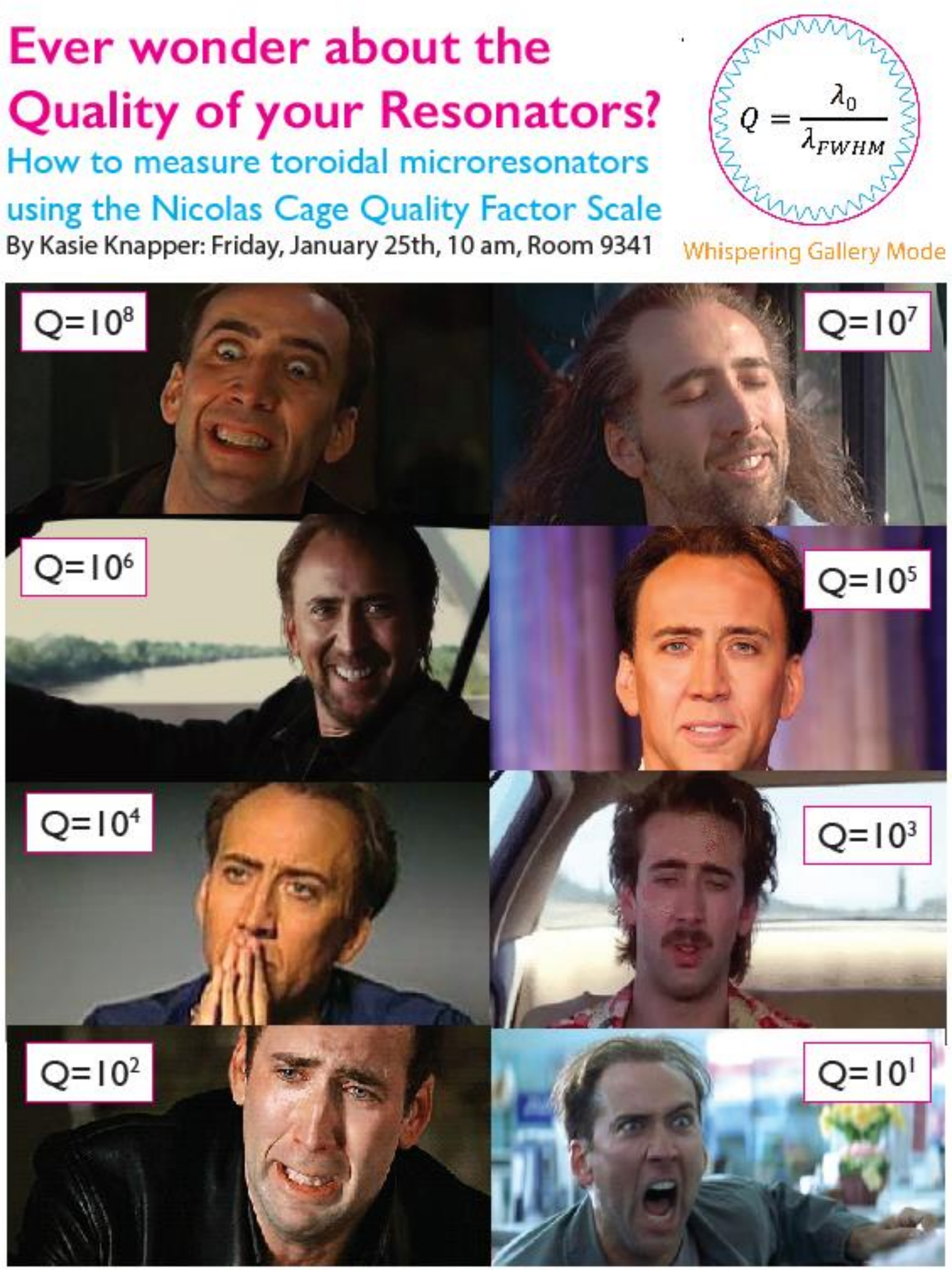
L. Xu, X. Jiang, G. Zhao, D. Ma, H. Tao, Z. Liu, F. G. Omenetto, L. Yang, *Opt. Express* **2016**, *24*, 20825.



K. A. Knapper, K. D. Heylman, E. H. Horak, R. H. Goldsmith, *Adv. Mater.* **2016**, *28*, 2945

Getting to Ultrahigh-Q is not easy





Ever wonder about the Quality of your Resonators?

How to measure toroidal microresonators using the Nicolas Cage Quality Factor Scale

By Kasie Knapper: Friday, January 25th, 10 am, Room 9341

$$Q = \frac{\lambda_0}{\lambda_{FWHM}}$$

Whispering Gallery Mode

$Q=10^8$

$Q=10^7$

$Q=10^6$

$Q=10^5$

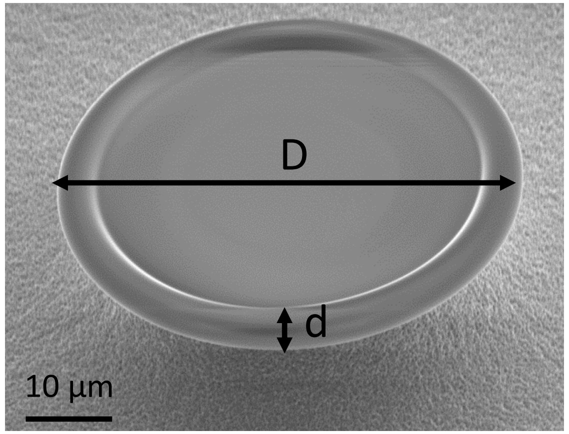
$Q=10^4$

$Q=10^3$

$Q=10^2$

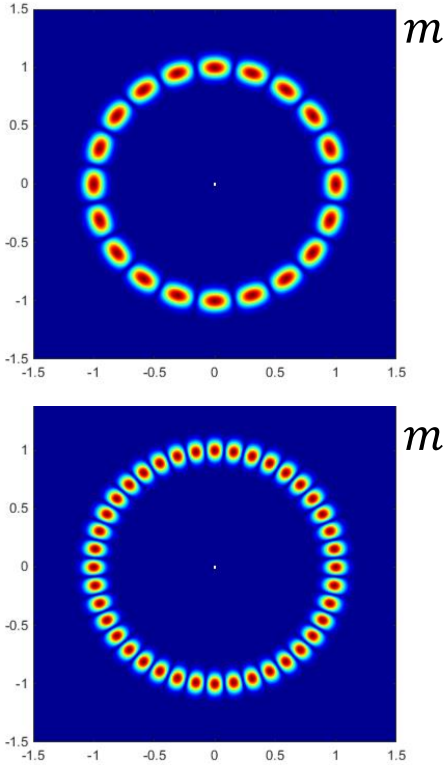
$Q=10^1$

Spatial Modes



$$\lambda = \frac{2\pi r n}{m}$$

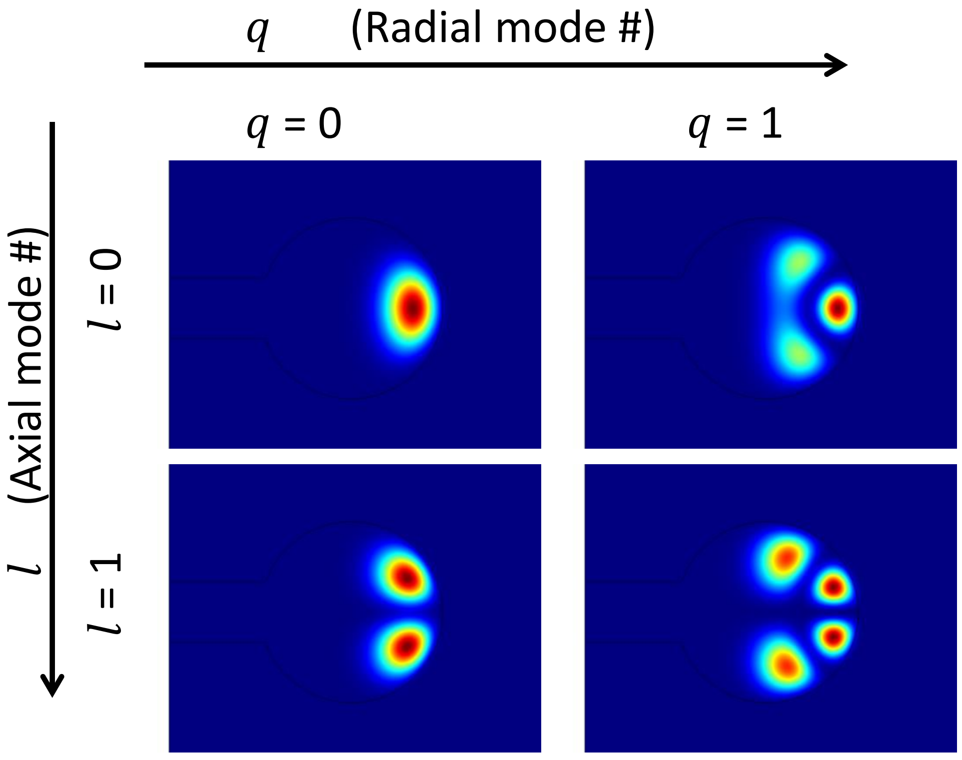
m (Azimuthal mode #)

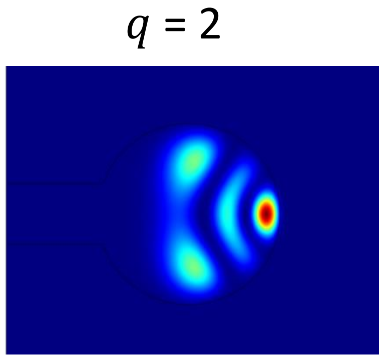


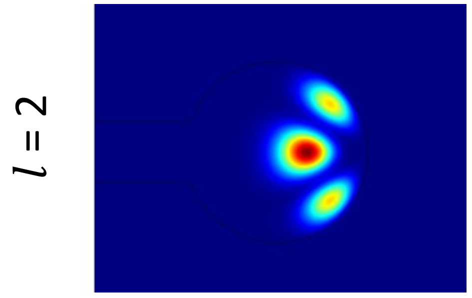
$m = 10$

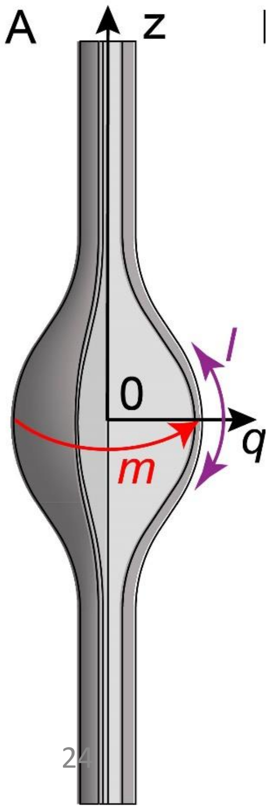
$m = 20$

q (Radial mode #)









WGM Notes

Occasionally referred to as “Travelling Wave” Resonators (no well-defined nodes without defects)

Early modern work on microspheres from Ilchenko (Moscow, JPL)

V.S. Ilchenko and co-workers (1989). *Physics Letters A, 137, 393*

Coupling via prism or tapered optical fiber

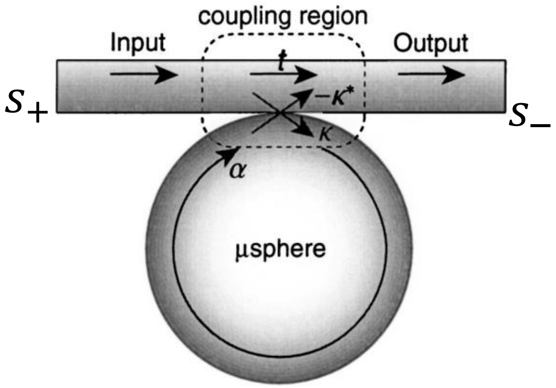
Fiber coupling has many advantages: mode filtering, mode matching, control of coupling (critical coupling @ $\omega = \omega_e$)

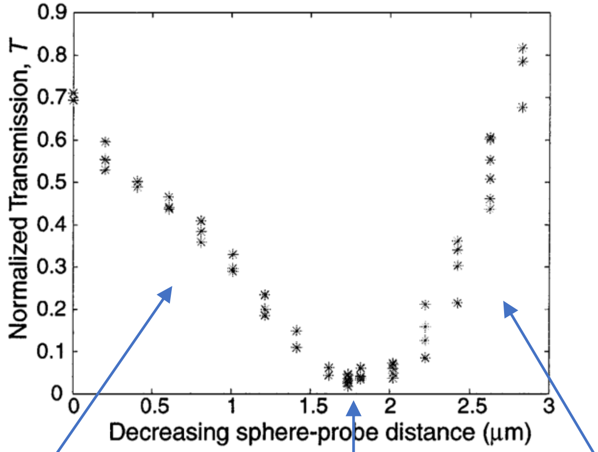
$$\Gamma = \frac{s_-}{s_+} = \frac{\frac{1}{\tau_0} - \frac{1}{\tau_e}}{\frac{1}{\tau_0} + \frac{1}{\tau_e}}$$

Haus, “Waves and Fields in Optoelectronics”, 1984, Prentice-Hall

Microspheres generally “one at a time”, vs on-chip toroids

On-chip toroids allow photonic integration (sort of)



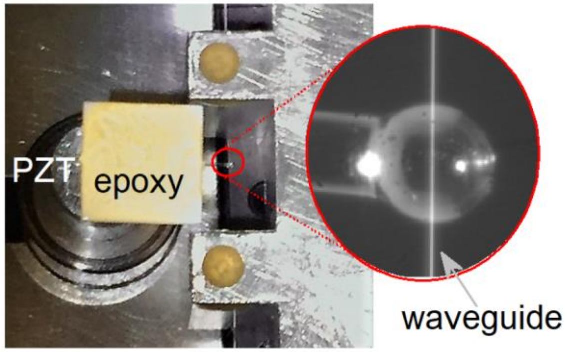


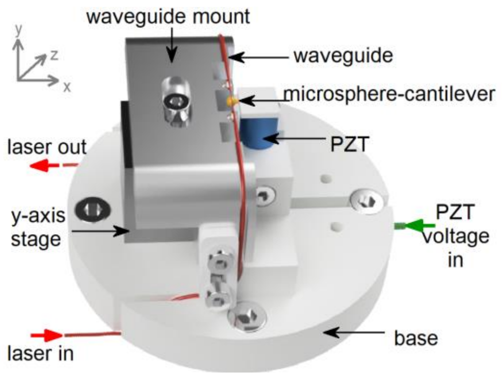
Over-coupled

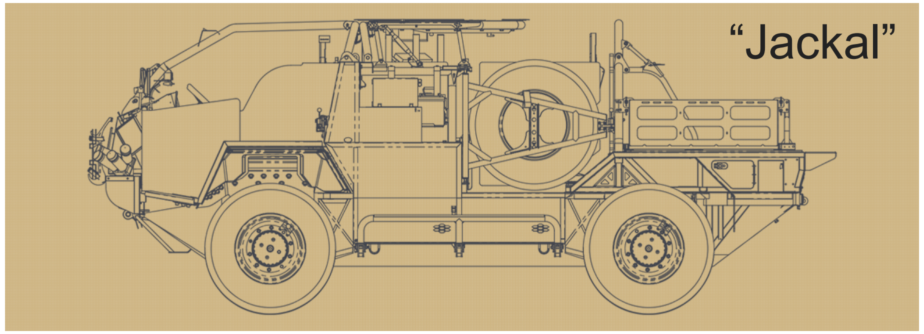
Critically coupled

Under-coupled

Cai, M., Painter, O. and Vahala, K.J., 2000. *Physical review letters*, *85*, 74.





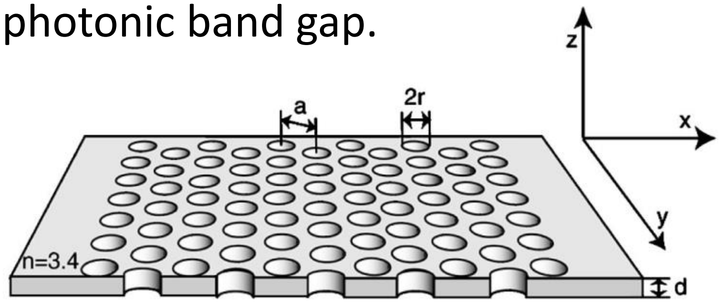


Li, Y. L., & Barker, P. F. (2018). *Sensors*, *18*(12), 4184.

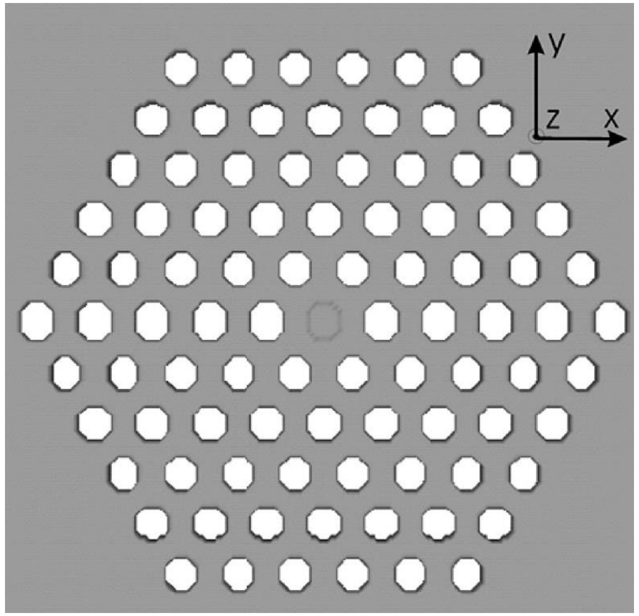
https://www.yingliali.com/

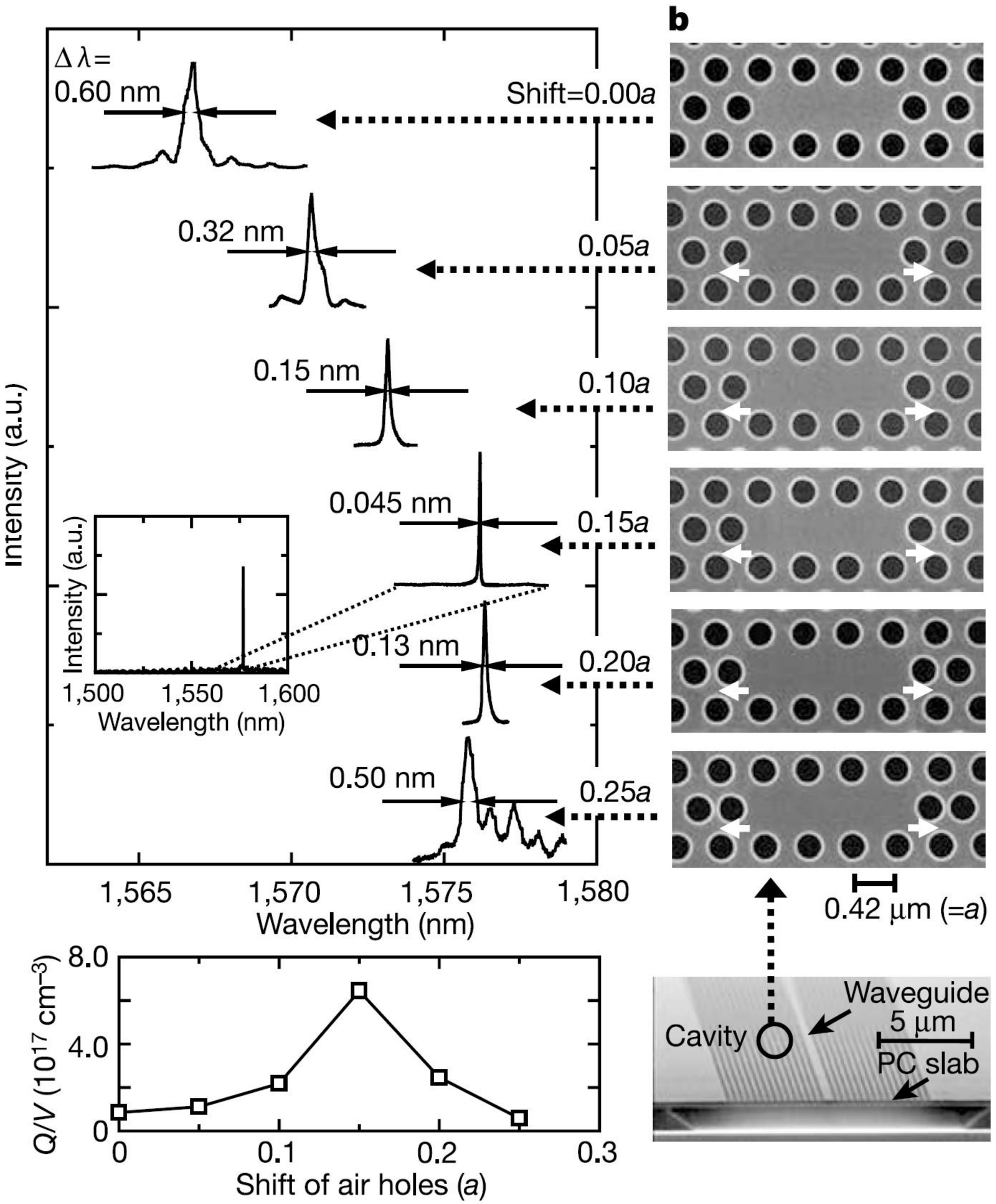
2D Photonic Crystal Micro(nano)cavities

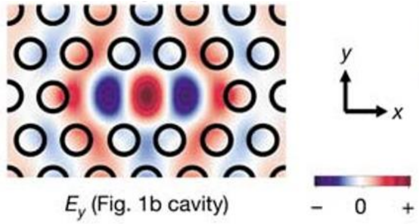
Imagine a periodic nanostructure with a photonic band gap.



Add in a defect, microcavity is confined by the surrounding band gap!



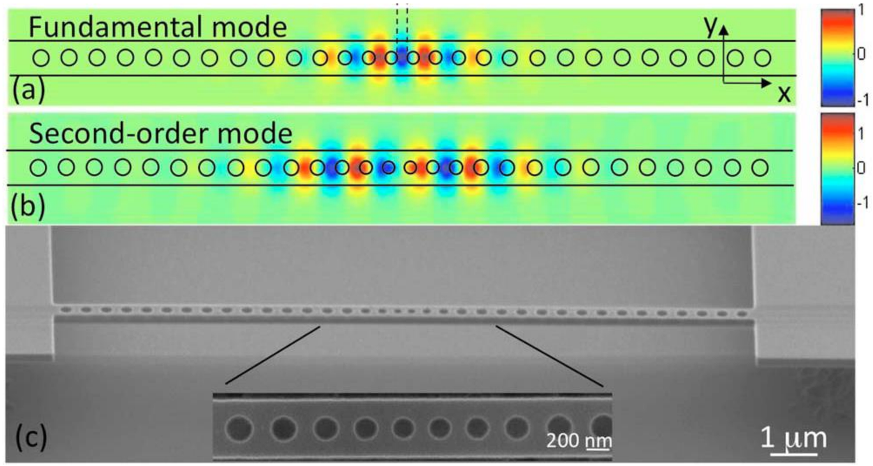




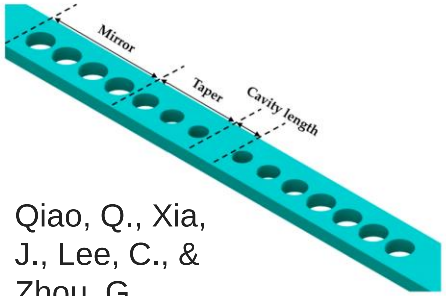
Vučković, J., Lončar, M., Mabuchi, H., & Scherer, A. (2001). *Physical Review E*, *65*(1), 016608.

Akahane, Y., Asano, T., Song, B. S., & Noda, S. (2003). *Nature*, *425*(6961), 944-947.

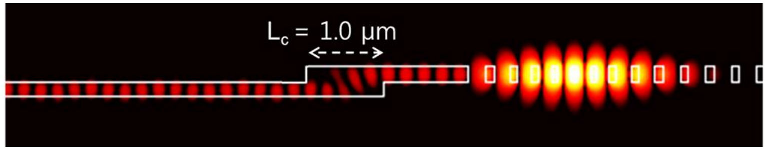
1D Photonic Crystal Micro(nano)cavities; Nanobeams!

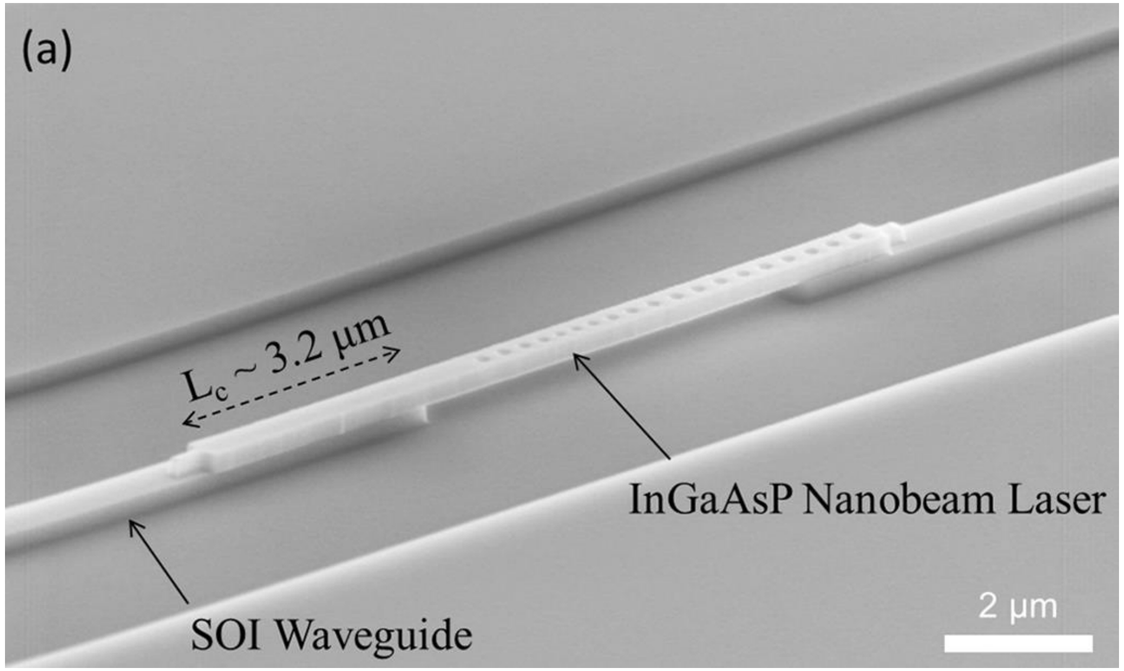


Deotare, P. B., McCutcheon, M. W., Frank, I. W., Khan, M., & Lončar, M. (2009). *Applied Physics Letters*, *94*(12), 121106.



Qiao, Q., Xia, J., Lee, C., & Zhou, G. (2018). *Micromachines*, *9*(11), 541.



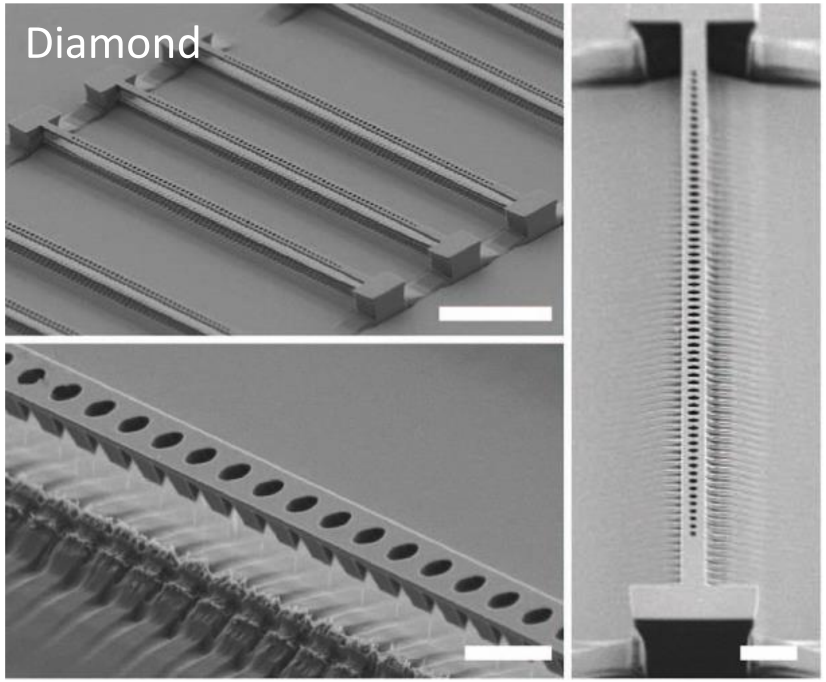


Lee, J., Karnadi, I., Kim, J. T., Lee, Y. H., & Kim, M. K. (2017). *ACS Photonics*, *4*(9), 2117-2123

Arrays of holes = Bragg mirrors

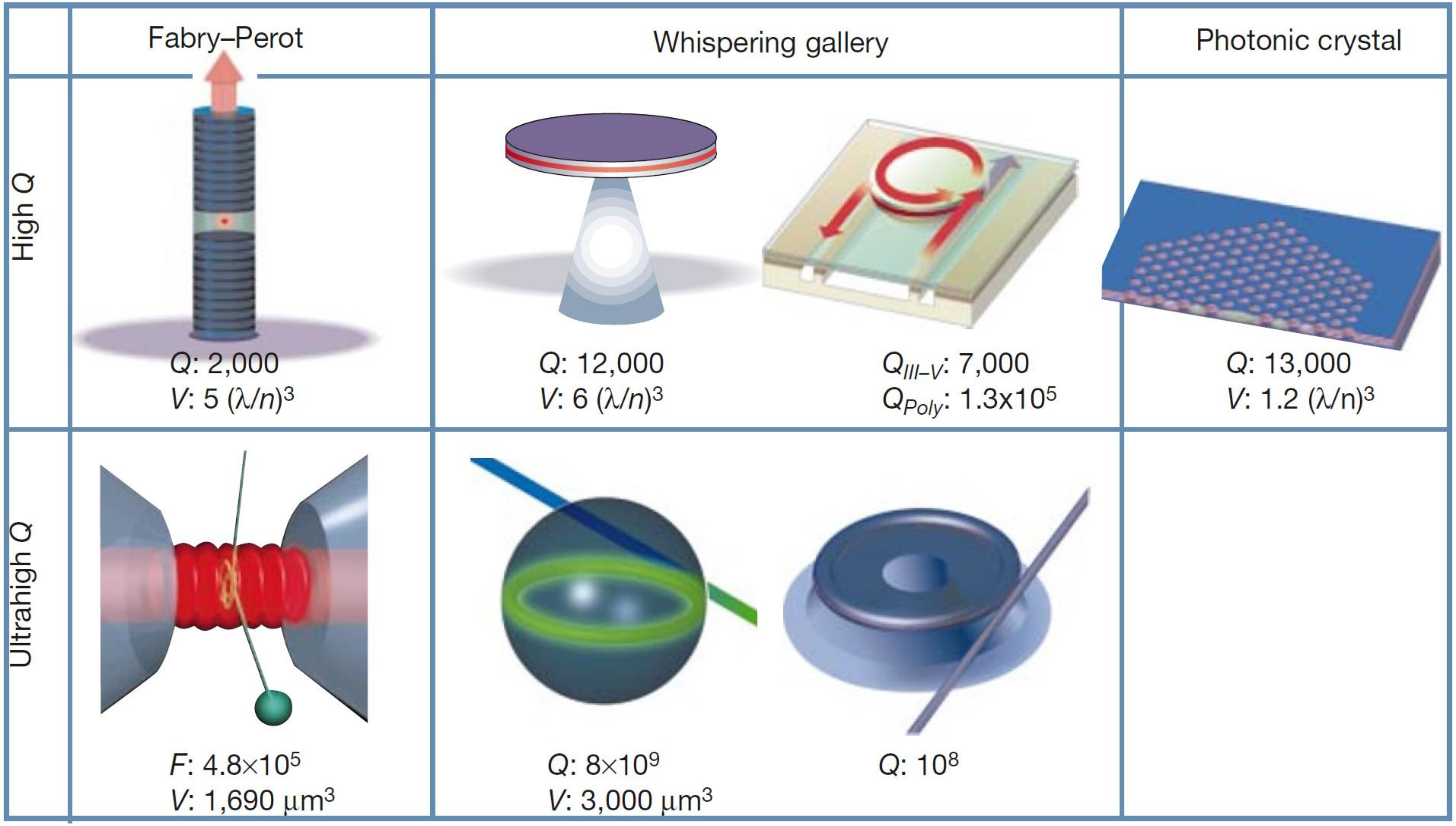
“zero volume” microcavity

Current frontier: integrating multiple exotic materials (InGaAsP, $LiNbO_3$, diamond) into more traditional photonic platforms



Burek, M. J., Chu, Y., Liddy, M. S., Patel, P., Rochman, J., Meesala, S., ... & Lončar, M. (2014). *Nature Comm*, *5*(1), 1-7.

Microcavity Menagerie



	Fabry–Perot	Whispering gallery		Photonic crystal
High Q	Q: 2,000 V: 5 $(\lambda/n)^3$	Q: 12,000 V: 6 $(\lambda/n)^3$	Q_{III-V}: 7,000 Q_{Poly}: $1.3\text{x}10^5$	Q: 13,000 V: 1.2 $(\lambda/\text{n})^3$
Ultrahigh Q	F: 4.8×10^5 V: 1,690 μm^3	Q: 8×10^9 V: 3,000 μm^3	Q: 10^8	

Vahala, Nature, 424, 83, 2003

What is any of this good for? QIS

Photons are great "flying" qubits because they interact weakly with matter

Photons are terrible "stationary" qubits because they interact weakly with matter

How to increase "interaction strength" between photons and quantum systems (atoms, molecules, QDs, defects)?

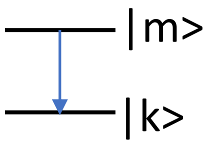
Solution: Cavity Quantum Electrodynamics (cQED)

How to think about spontaneous emission of a photon (from a molecule)?

Differential Transition Rate

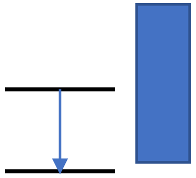
$$\Gamma_{m\to k} = \frac{2\pi}{\hbar}|V_{m\to k}|^2\rho(\omega)$$

Fermi's Golden Rule



$\langle m|\vec{\mu}|k\rangle$

Transition dipole moment (matrix element) lives in here



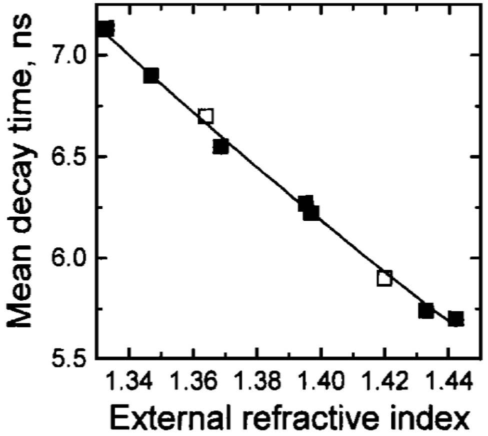
$\rho(E)$ Photonic density of states (PDOS), all the ways (ie, different k vectors) of coupling to photons

For free space:

$$\rho(\omega) \propto \frac{\omega^2}{\pi c^3}$$

Is this actually interesting? Hard to change.

As n(refractive index)↑;c↓;$\rho(\omega)$ ↑

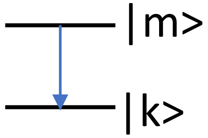


Petrov, E. P., Kruchenok, J. V., & Rubinov, A. N. (1999). *J. Fluor.*, *9*, 111.

Schatz and Ratner, "Quantum Mechanics in Chemistry," Dover, 2002

The Purcell Effect

$$\Gamma_{m\to k} = \frac{2\pi}{\hbar}|V_{m\to k}|^2\rho(\omega)$$



For free space:

$$\rho_{FreeSpace}(\omega) \propto \frac{\omega^2}{\pi c^3}$$

For a cavity:

$$\rho_{Cavity}\,(\omega) \propto \frac{c}{2\pi QV}\frac{3}{\left(\frac{c}{2Q}\right)^2 + (\omega_{cav}-\omega)^2}$$

$@\ \omega \neq \omega_{cav}$

$$\frac{\Gamma_{Cavity}}{\Gamma_{FreeSpace}} = \frac{\rho_{Cavity}}{\rho_{FreeSpace}} = \frac{3}{16\pi^2 Q}\frac{\lambda^3}{V}$$

Suppressed emission!
Can’t emit in a band gap!

$@\ \omega = \omega_{cav}$

$$\frac{\Gamma_{Cavity}}{\Gamma_{FreeSpace}} = \frac{\rho_{Cavity}}{\rho_{FreeSpace}} = \frac{3Q}{4\pi^2}\frac{\lambda^3}{V} = F_P$$

Purcell Factor

Enhanced emission rate!
For real!

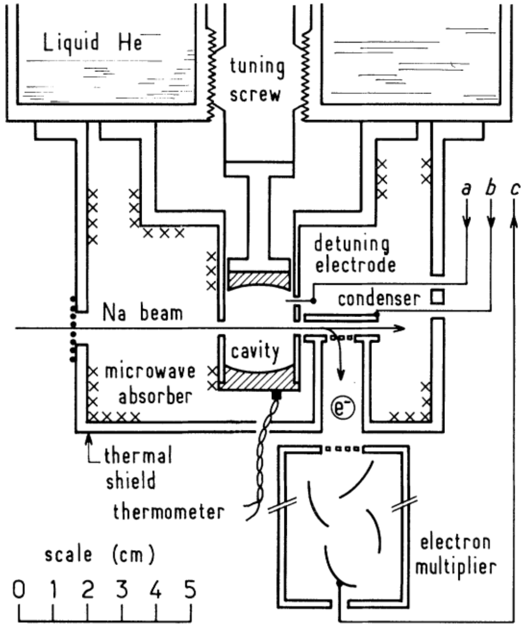
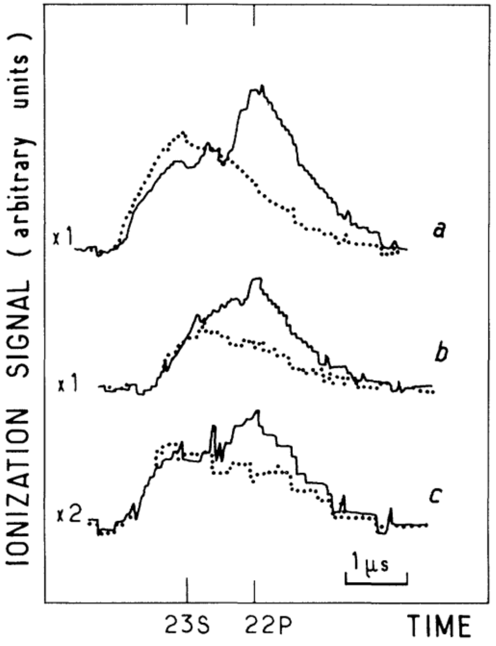


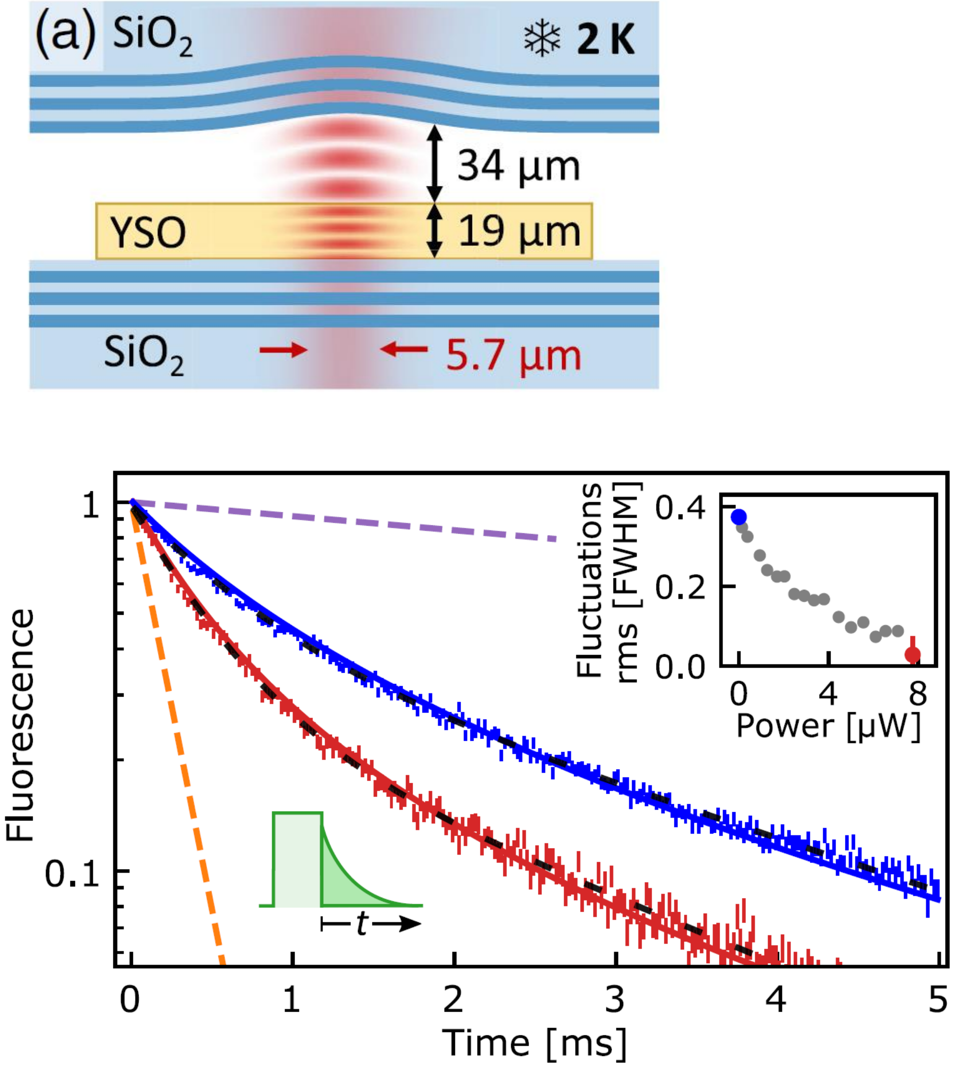
FIG. 1. Experimental arrangement.

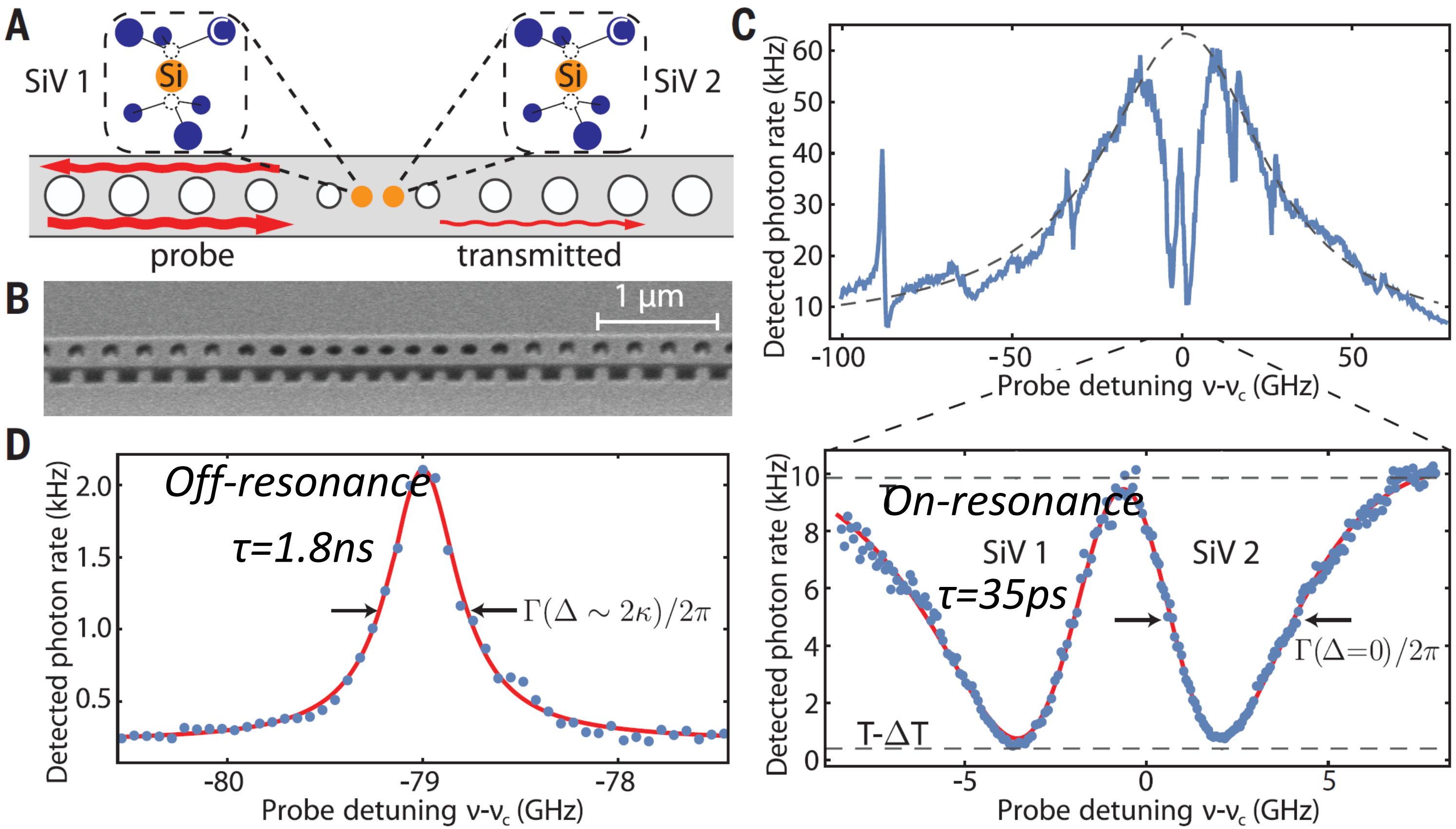


Goy, P., Raimond, J. M., Gross, M., & Haroche, S. (1983). *Physical Review Letters*, *50*, 1903.

Barnes, W. L., Horsley, S. A., & Vos, W. L. (2020). states. *Journal of Optics*, *22*(7), 073501.
O. Benson, Quantenoptik09, https://www.physik.hu-berlin.de/de/nano/lehre/copy_of_quantenoptik09/Chapter12

Radiative Engineering via the Purcell Effect, Solid State Defects

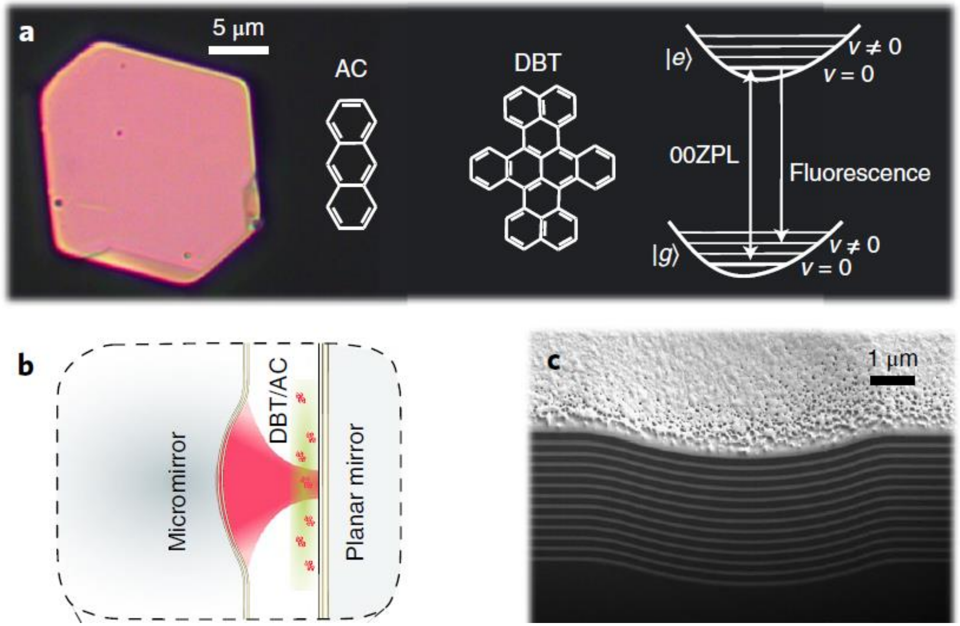


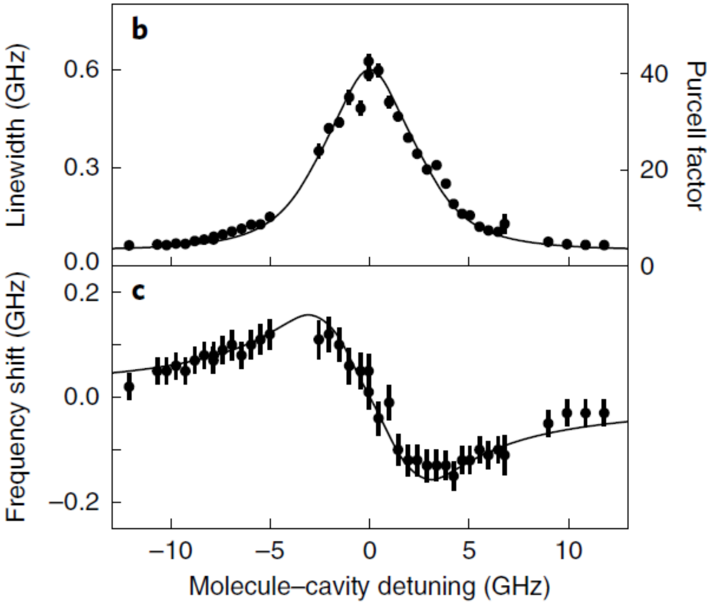


Reiserer, Merkel, and co-workers, PRX, **2020**, 041025

Evans, Lončar, Lukin, and co-workers, Science, **2018**, 362, 662

Radiative Engineering via the Purcell Effect, Molecules





Wang, Sandoghdar, and co-workers, Nature Photonics, **2019**, 15, 483

What do you get?

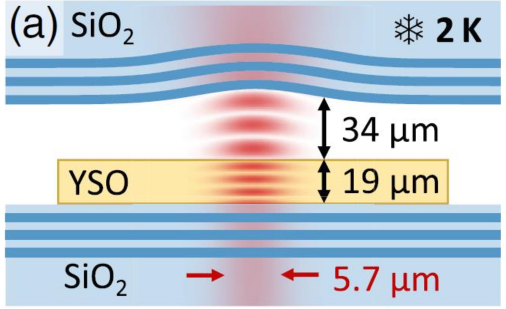
Outcompete relaxation to other (vibronic) states which broadens emission spectrum (photons are more identical)

Faster photon count rates means more information can be transferred, more operations/second

More exotic physics in the “strong coupling” regime

Pro and Cons of Microcavities for QIS

$$F_P = \frac{3Q}{4\pi^2}\frac{\lambda^3}{V}$$



Not necessarily the same microcavity!

Fabry-Perot

Q up to 10^7
V down to <10µm^3

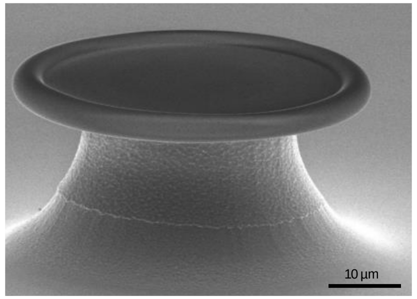
Good news: tunable resonances!

Bad news: tunable resonances! Instability!

Excellent mode overlap

Used in both large L (ions/Rydberg atoms) and small L (defects) limits

Requires Expen$ive Optical Coating$, restricts geometry



WGM

Q up to >10^8
V down to 100's of µm^3

Not easily tunable

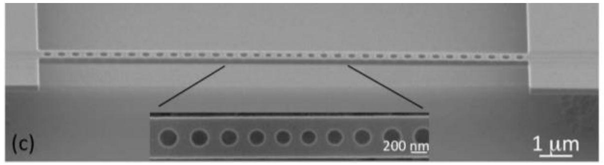
Need to get smooth, limits Q for some materials

Can't make too small, get radiative losses (depends on material, n)

Weak coupling, unless defects are doped inside

Queens of Q's

Fascinating applications in optomechanics



Photonic Crystal/Nanobeam

Q up to ~10^5
V down to <0.6 µm^3

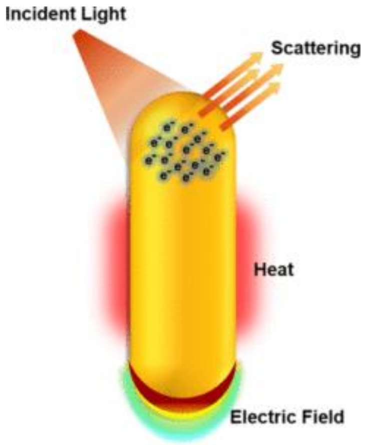
Not easily tunable

Need to get fabrication defect-free (theoretical Q's ~10^7)

Weak coupling, unless defects are doped inside

Super Low V's (for dielectric)

Fascinating applications in optomechanics

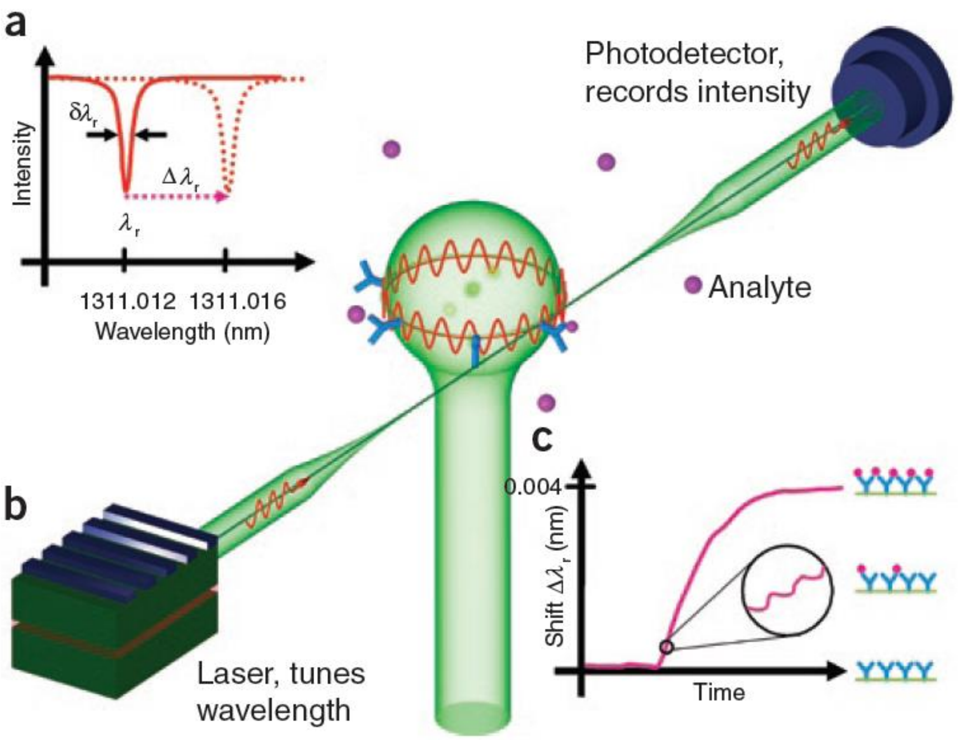


Plasmonic "Nanocavity"

Q up to 10?
V down to 10^{-6} µm^3

Acc. Chem. Res. 2019, 52, 8, 2124−2135

What is any of this good for? Sensing and Spectroscopy



Vollmer and Arnold, *Nature Methods.*, **2008**, *5*, 591.

K. D. Heylman; K. A. Knapper; E. H. Horak; M. T. Rea; S. K. Vanga; R. H. Goldsmith. **Optical Microresonators for Sensing and Transduction: A Materials Perspective**. *Advanced Materials* **2017**, *29*.

Important Benchmarks (not inclusive):

Single Particle Detection

Li, Xiao, and coworkers, *PNAS*, **2014**, *111*, 14657.

Ozdemir, Yang, and coworkers, *PNAS*, **2014**, *111*, 3836.

Lu, Vahala, and coworkers, *PNAS*, **2011**, *108*, 5976.

Swaim, Bowen, and coworkers, *APL*, **2013**, *103186*.

Single Protein Detection

Dantham, Arnold, and coworkers, *Nano Lett.*, **2013**, *13*, 3347.

Yu and Lu, *Nature Comm*., **2016**, 7, 12311.

Single DNA oligomer, Ion Detection

Baaske, Vollmer, and coworkers, *Nature Nanotech.*, **2014**, *9*, 933.

Baaske, Vollmer, and coworkers, *Nature Photon.*, **2016**, *10*, 733.

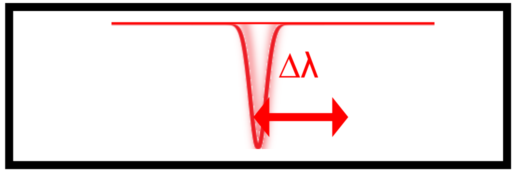
How do you know what molecule has bound?

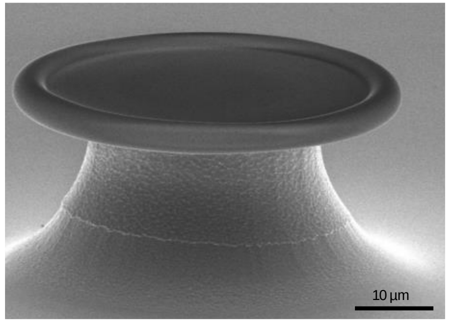
Surface Functionalization: Bailey, Armani, Hunt, etc.

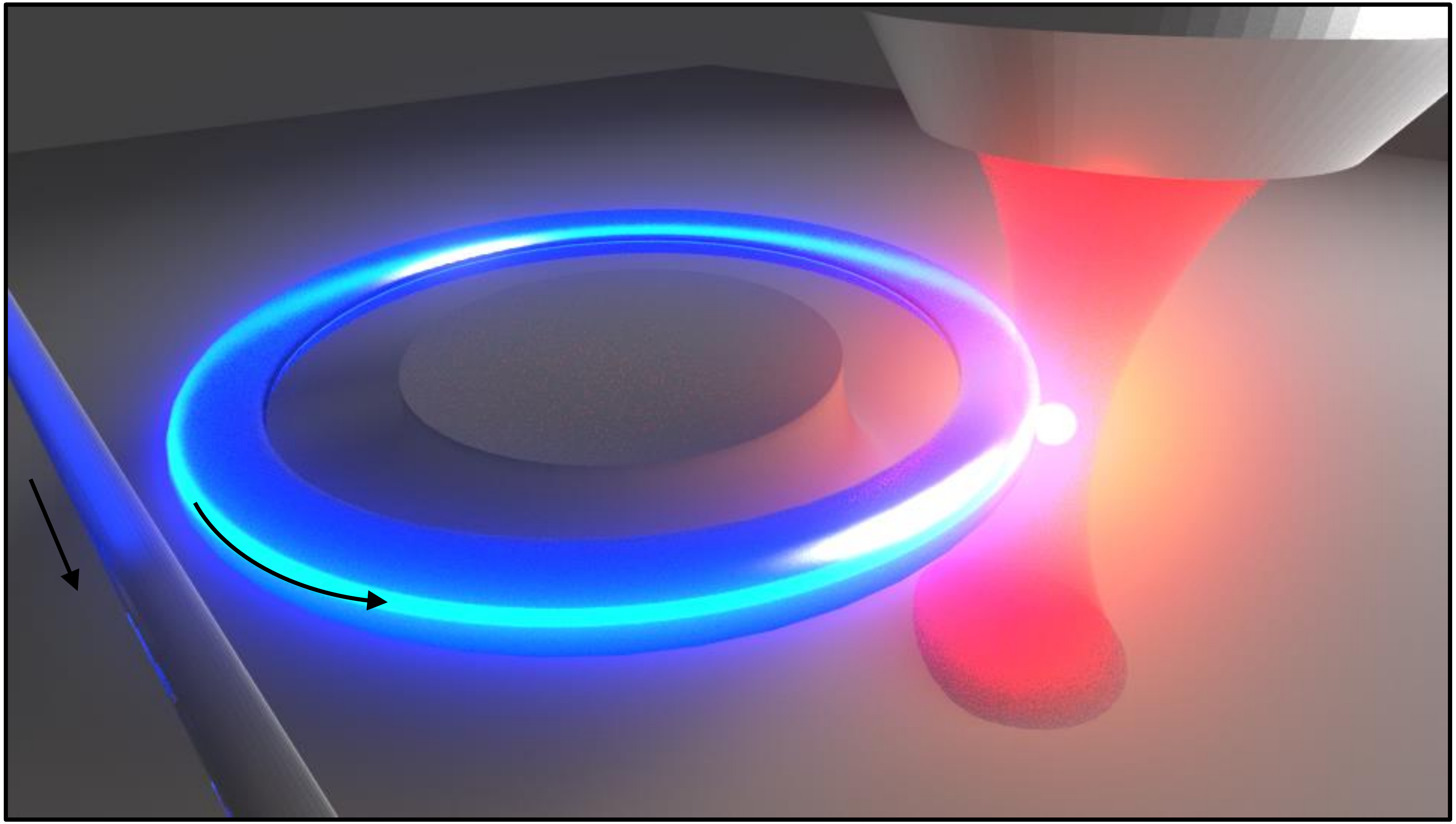
A means of performing *in situ* spectroscopy would allow single-molecule identification.

Optical Microresonator Spectrometers

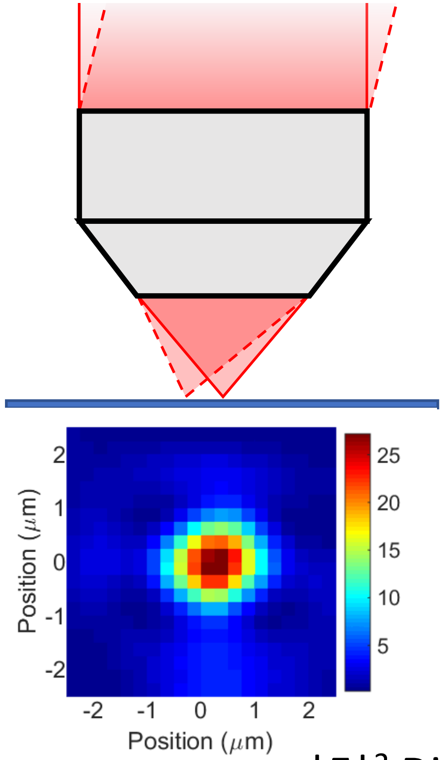
Fiber Transmission:



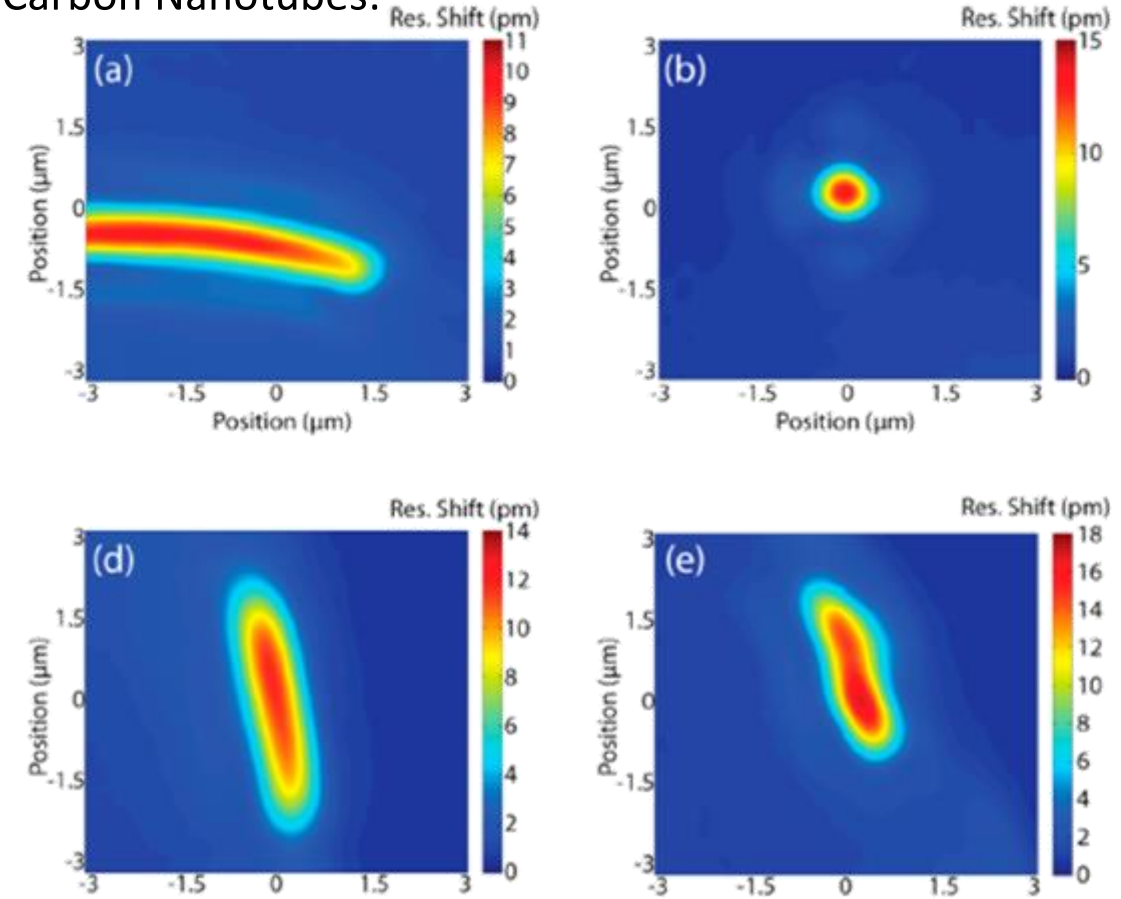


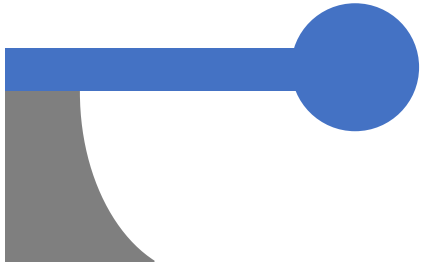


Photothermal Microscopy

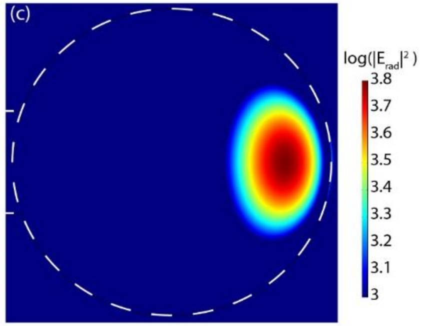


Carbon Nanotubes:

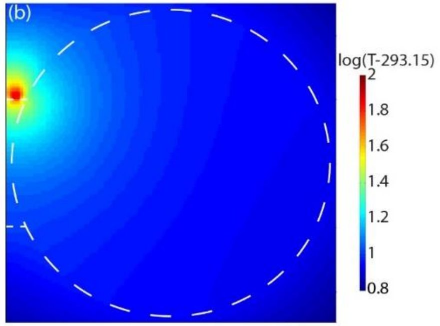




|E|^2 Distribution



Temperature Distribution

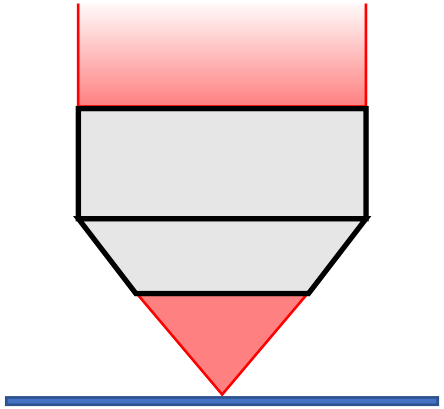


$\sigma = 2.3 \pm 0.5 \times 10^{-18}$ cm^2/C

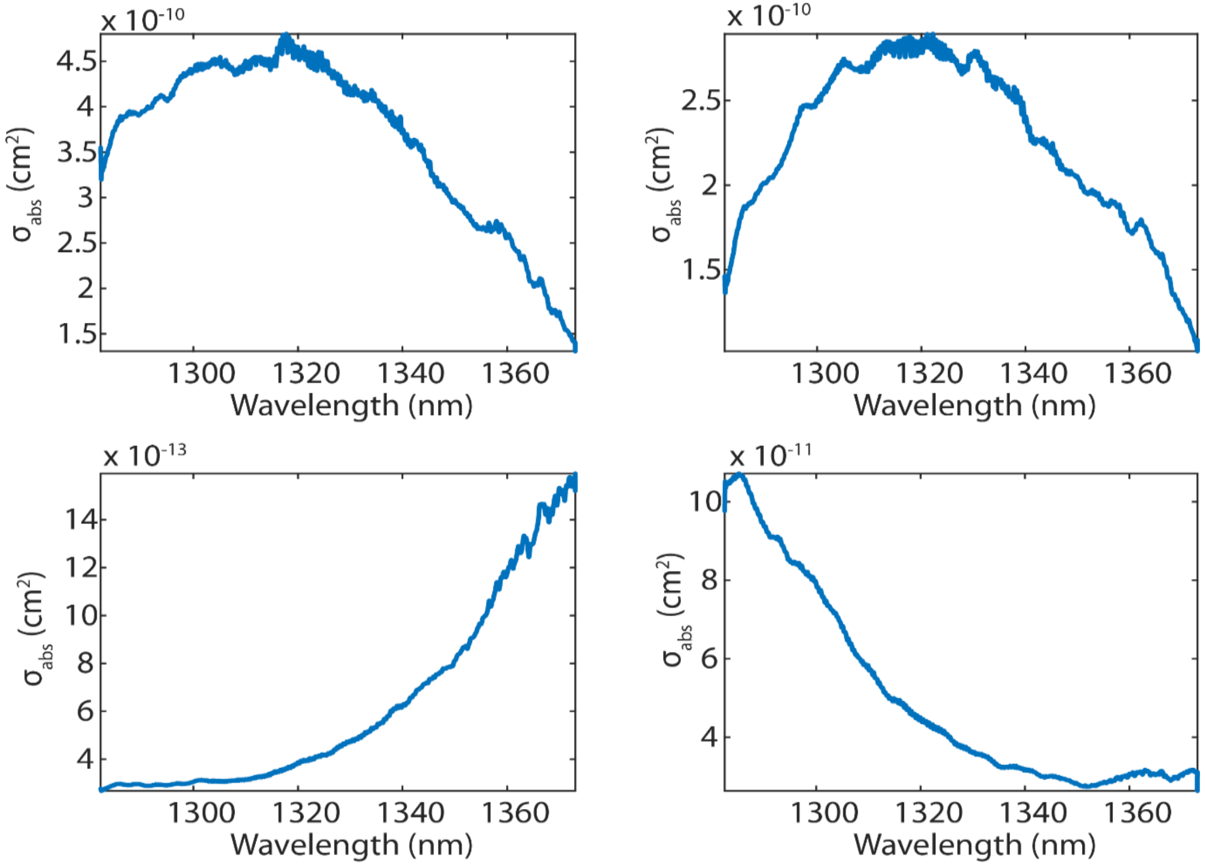
$\sigma_{BULK} = 2.5\text{-}2.8 \times 10^{-18}$ cm^2/C

Knapper, Heylman, Horak, and Goldsmith, *Advanced Materials*, 28, 2944, **2016**
Heylman, Knapper, and Goldsmith, *Journal of Physical Chemistry Letters*, 5, 1917, **2014**

Photothermal Spectroscopy



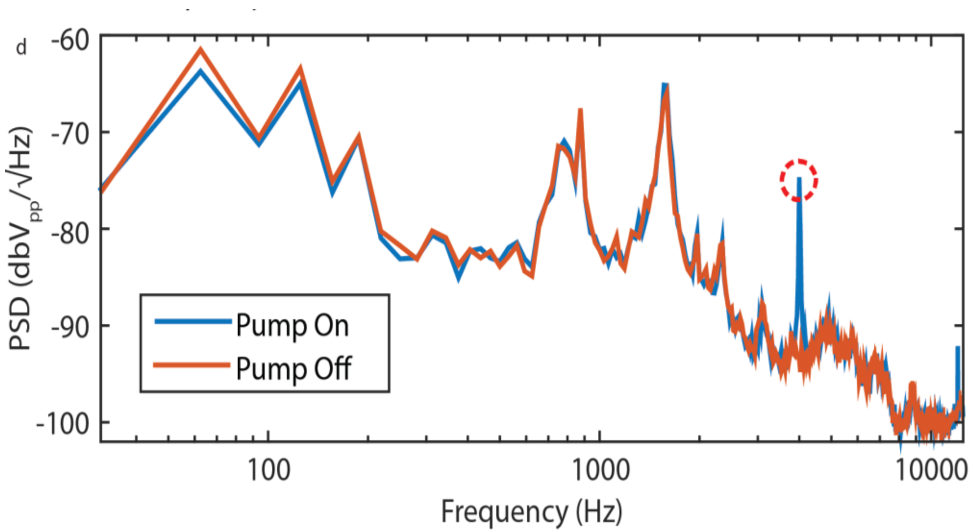
Gold Nanorods:

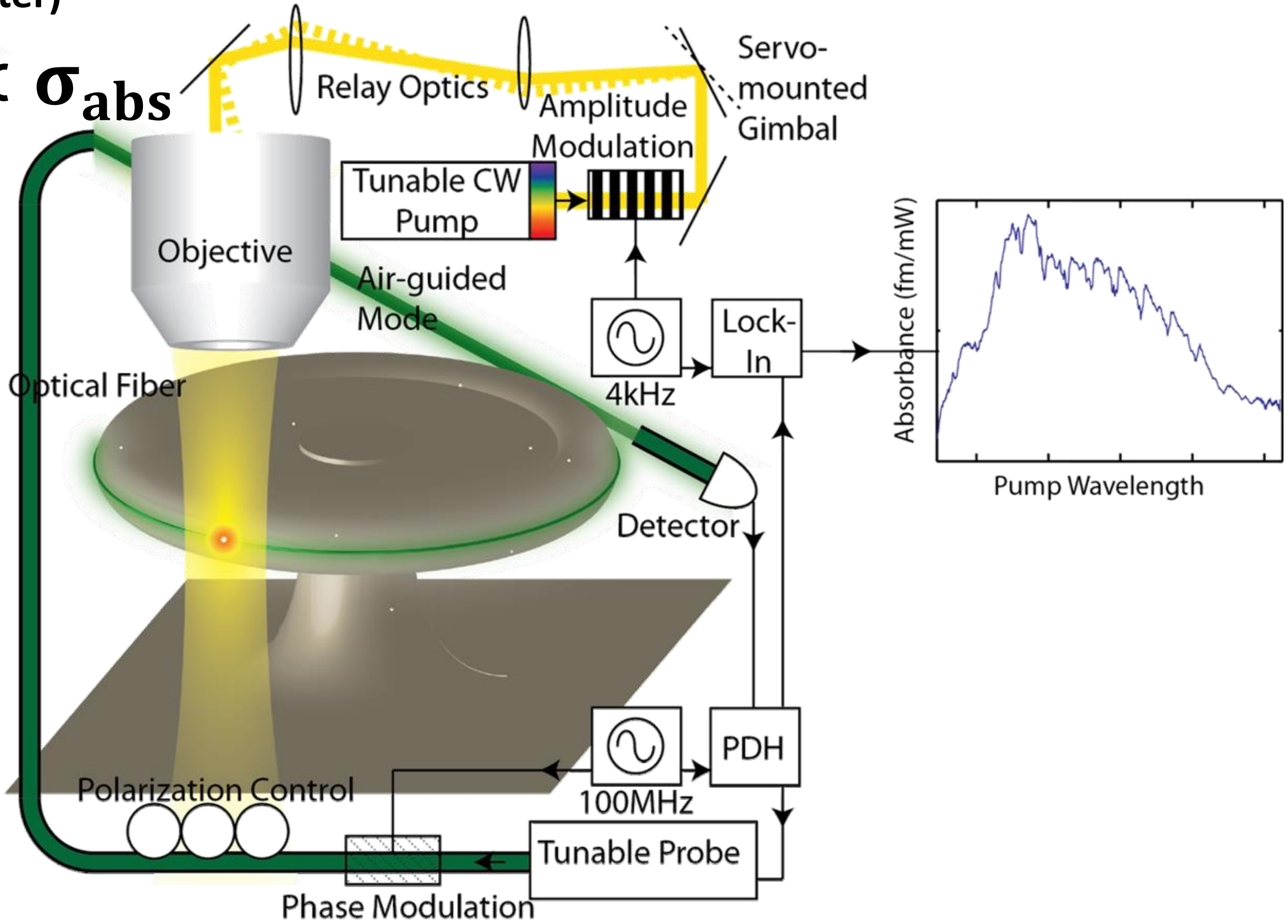


Heylman, Thakkar, Horak, Quillin, Cherqui, Knapper, Masiello, and Goldsmith, *Nature Photonics,* **2016**, 10, 788

Detect Resonator Frequency Shifts <100Hz (1 Attometer)

$$\Delta \boldsymbol{I} \propto \Delta\theta \propto \Delta\lambda \propto \Delta\mathbf{n} \propto \Delta\mathbf{T} \propto \boldsymbol{\sigma}_{\mathbf{abs}}$$





Heylman, Thakkar, Horak, Quillin, Cherqui, Knapper, Masiello, and Goldsmith, *Nature Photonics,* **2016**, 10, 788

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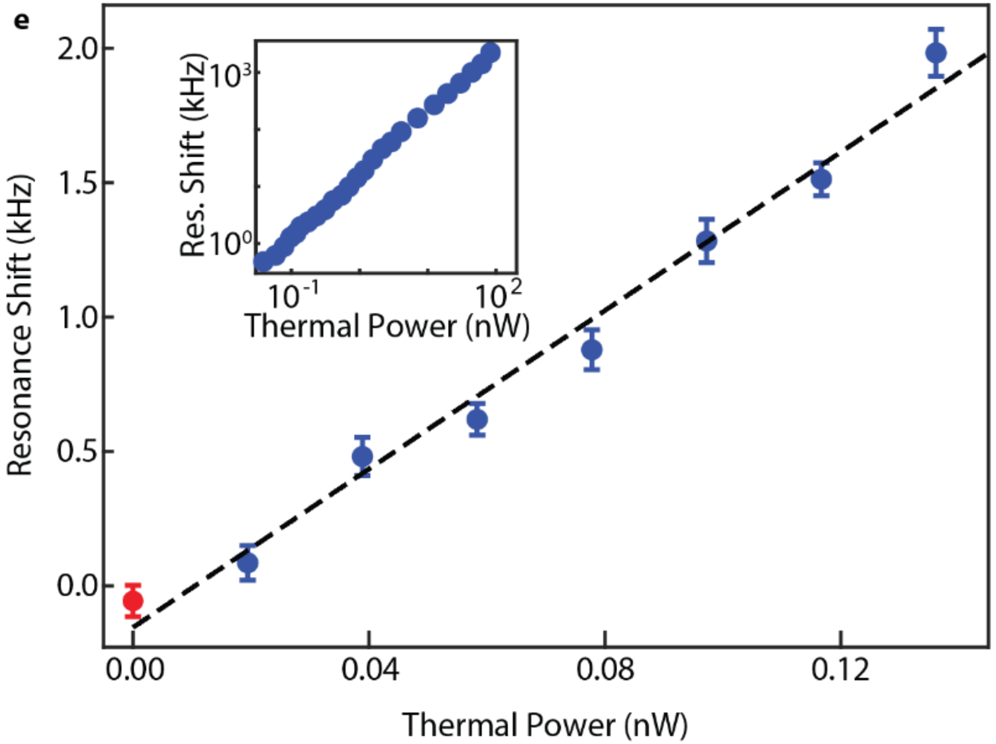
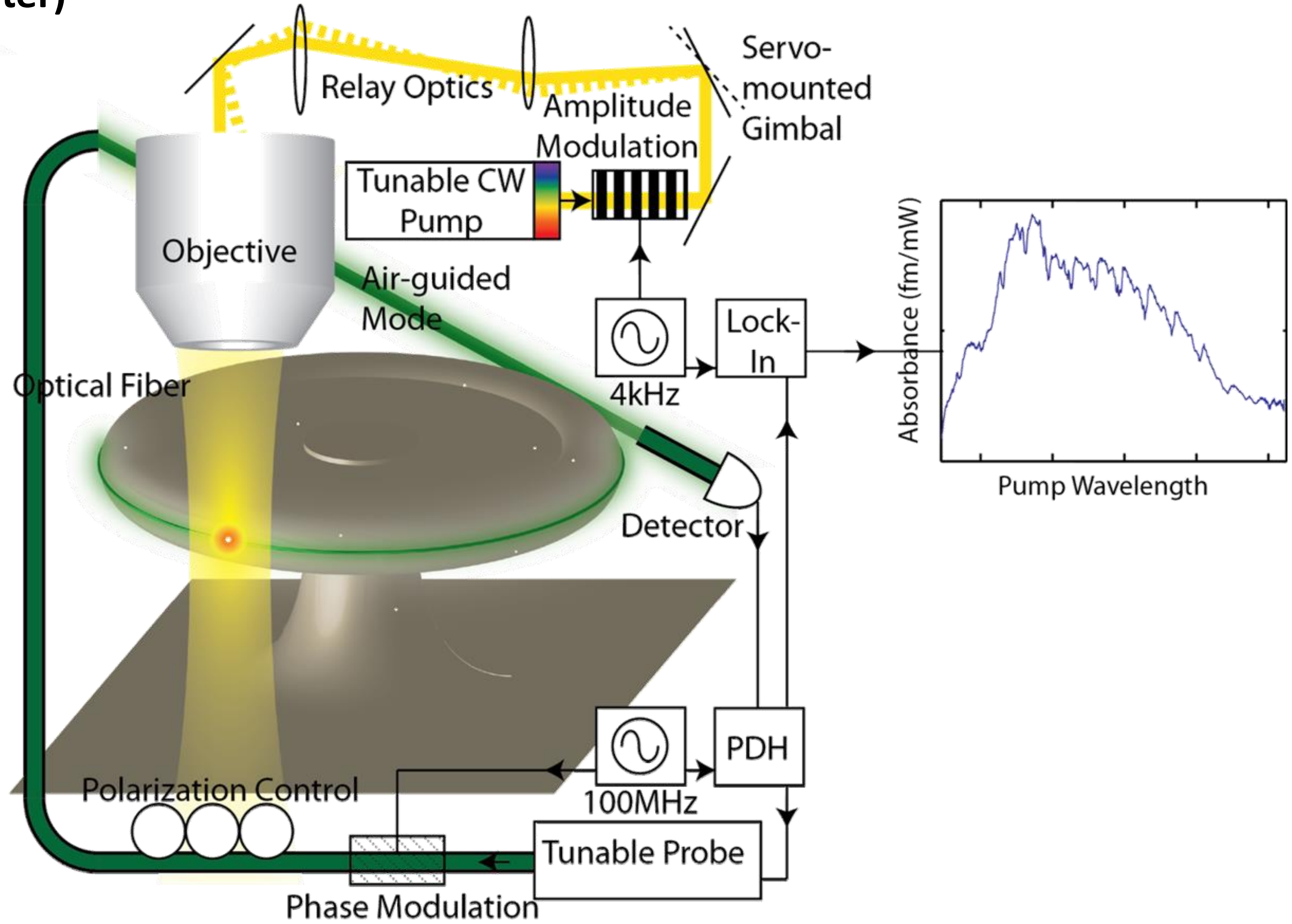




Pumping a Au Nanorod

Amplitude modulation, 4kHz

Lock-in Time Constant, 1s

Errorbars: STD of mean, 30 repeats

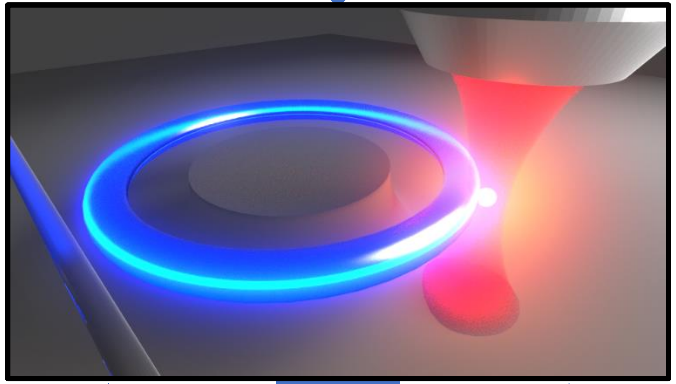
One dye molecule pumped to near saturation, 10nW→ 240 kHz shift

Largely immune to scattering

Background still high

Heylman, Thakkar, Horak, Quillin, Cherqui, Knapper, Masiello, and Goldsmith, *Nature Photonics,* **2016**, 10, 788

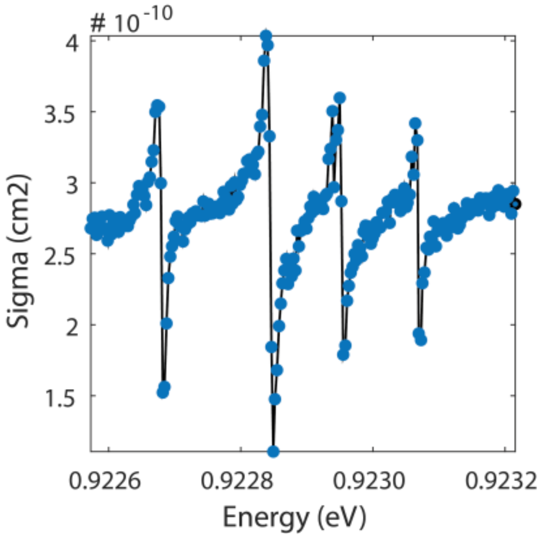
Microresonator Spectrometers



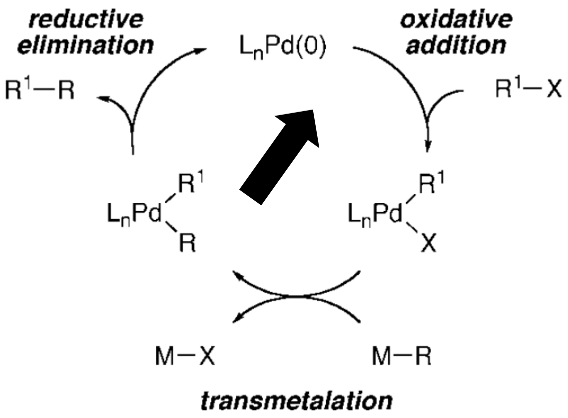
Nature Photonics., **2016,** 10, 788

Nano Lett., **2017,** 17, 6927

Nano Lett., **2020,** 20, 50



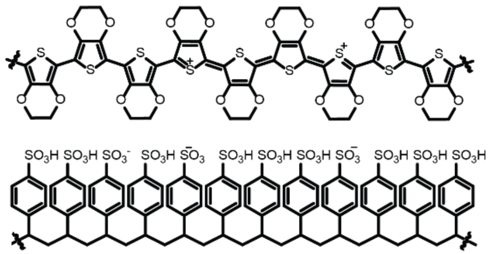
ACS Nano, **2019**, 13, 12743



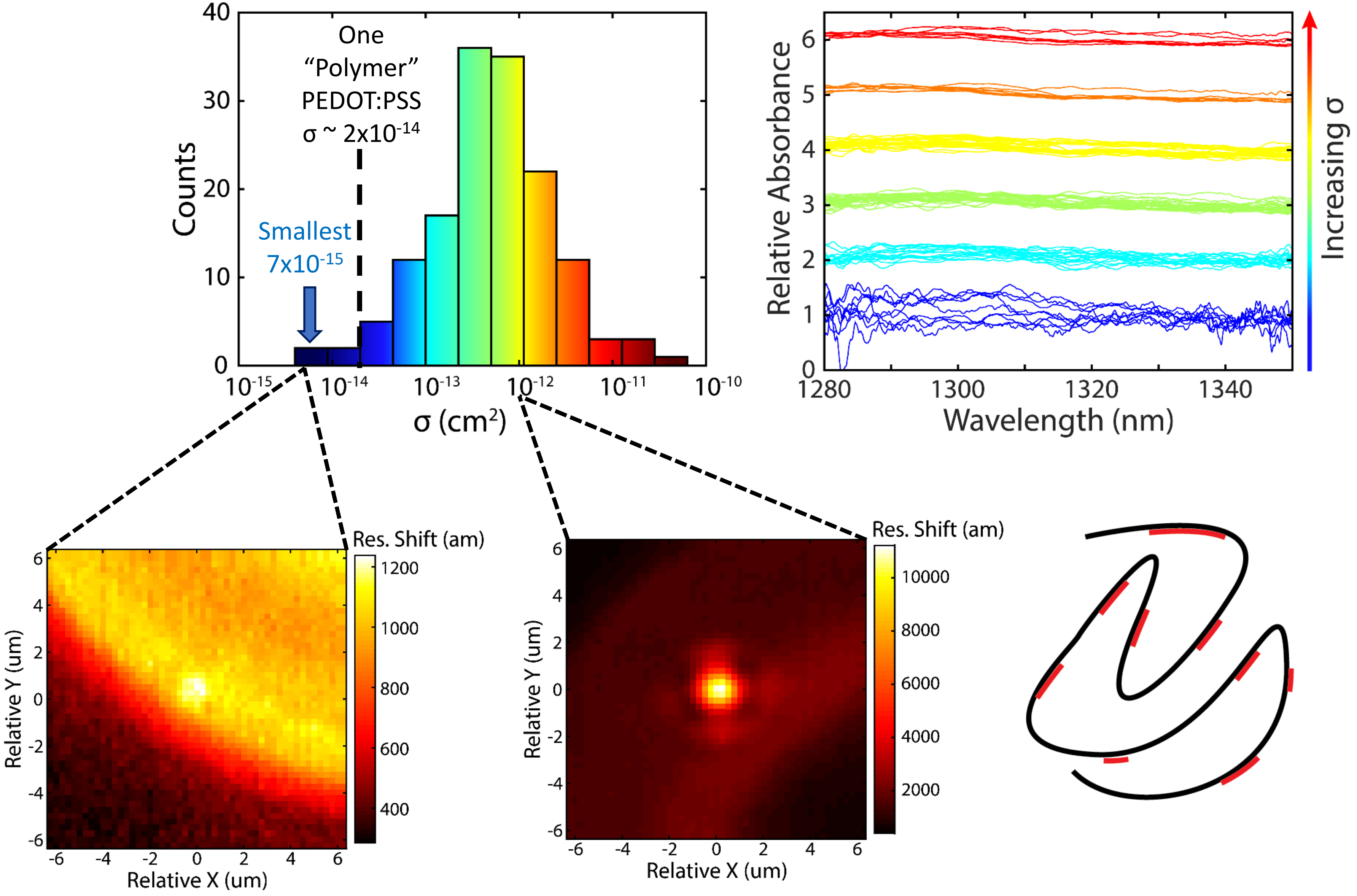
J. Phys. Chem. Lett, **2014**, 5, 1917

Nano Lett., **2018,** 18, 1600

J. Phys. Chem. C, **2019**, 123,30781

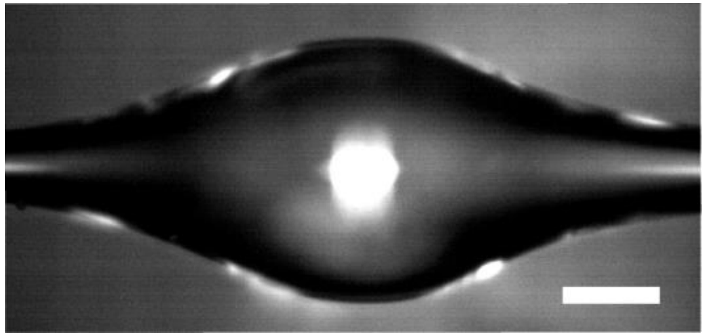


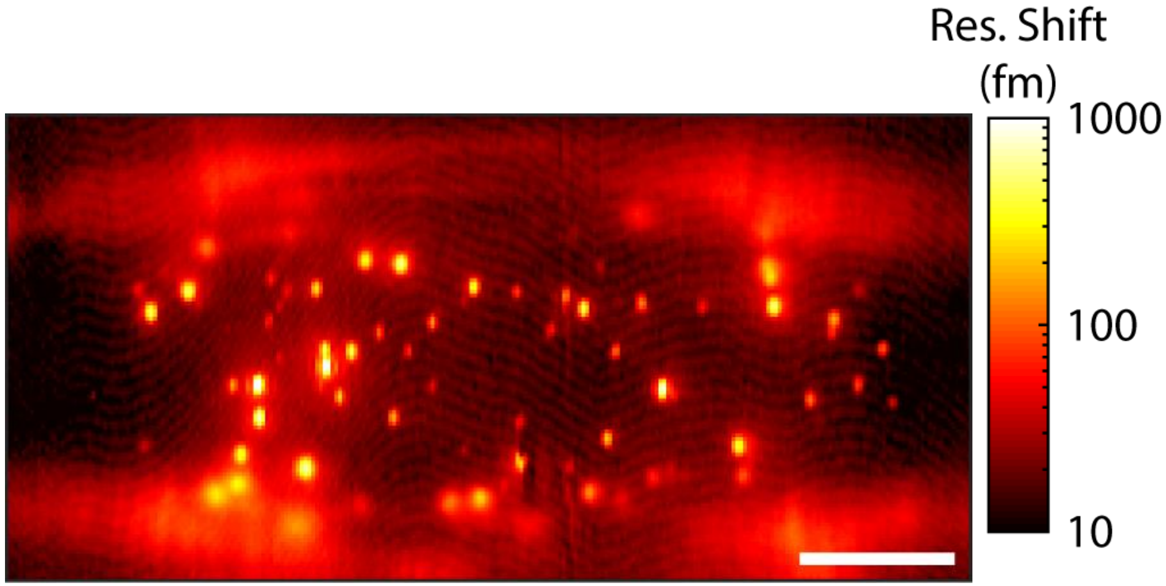
Single Polymer Spectroscopy

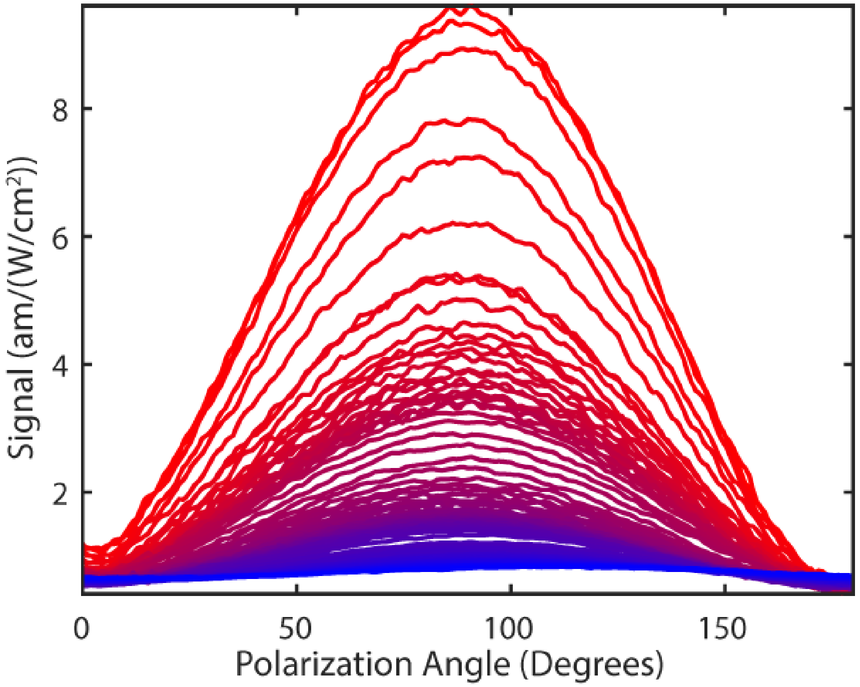


Horak, Rea, Heylman, more people, Gopalan, Wright, Aspuru-Guzik, and Goldsmith, *Nano Lett.,* **2018,** 18, 1600

Watching the Etching of a Single Nanorod via Absorption

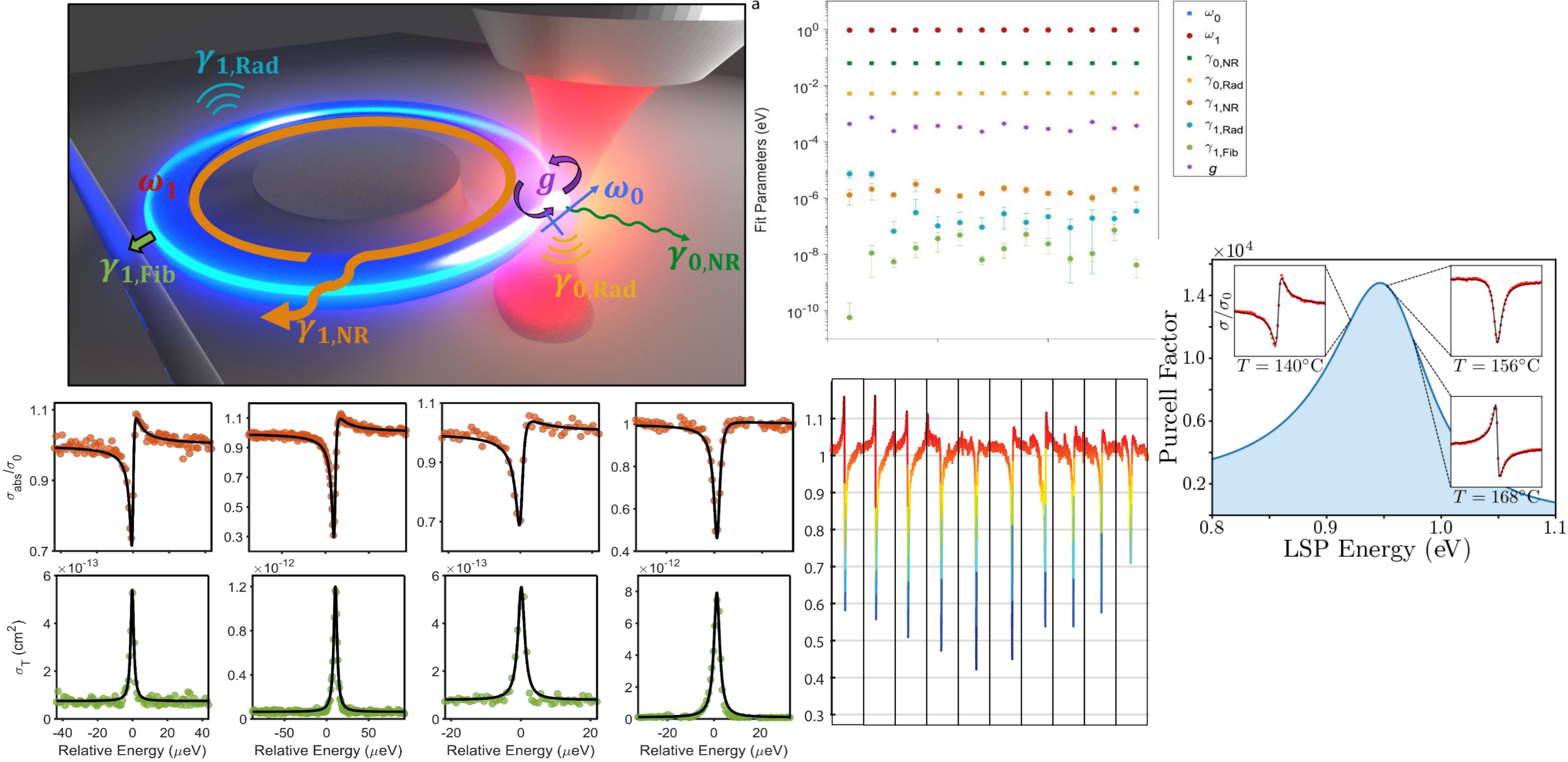






Hogan, Horak, Ward, Knapper, Nic Chormaic, and Goldsmith, *ACS Nano,* **2019**, 13, 12743

Hybrid Plasmonic-Photonic Systems



Thakkar, Rea, Smith, Heylman, Quillin, Horak, Knapper, Masiello, and Goldsmith, *Nano Lett.*, **2017,** 17, 6927
Pan, Smith, Nguyen, Knapper, Masiello, and Goldsmith, *Nano Lett.*, **2020**, 20, 50

Thanks!

Dr. Mike Mattei

Dr. Tzu-Ling Chen

Dr. Lisa-Maria Needham

Professor David Masiello

We are looking for postdocs! Come chat with me!

NIH

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