Reduced scattering losses in optical microcavities

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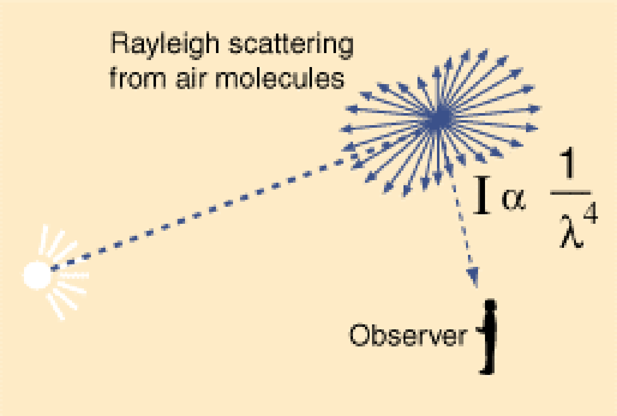
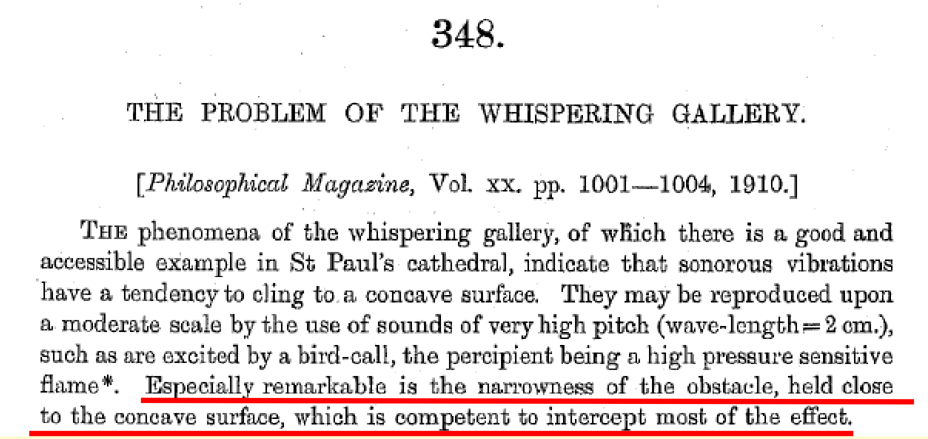
Historical note

Lord Rayleigh (1842-1919)
a.k.a. John William Strutt

1) Light scattering by small particles
(explained why the sky is blue)

2) First description of cavity modes
(whispering gallery modes)





348.

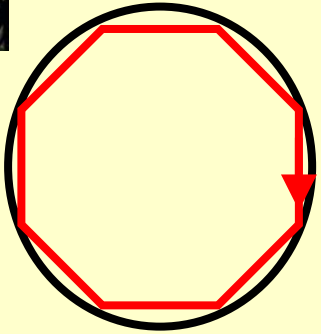
THE PROBLEM OF THE WHISPERING GALLERY.

[*Philosophical Magazine*, Vol. xx. pp. 1001—1004, 1910.]

The phenomena of the whispering gallery, of which there is a good and accessible example in St Paul's cathedral, indicate that sonorous vibrations have a tendency to cling to a concave surface. They may be reproduced upon a moderate scale by the use of sounds of very high pitch (wave-length = 2 cm.), such as are excited by a bird-call, the percipient being a high pressure sensitive flame*. Especially remarkable is the narrowness of the obstacle, held close to the concave surface, which is competent to intercept most of the effect.

St. Pauls cathedral whispering gallery

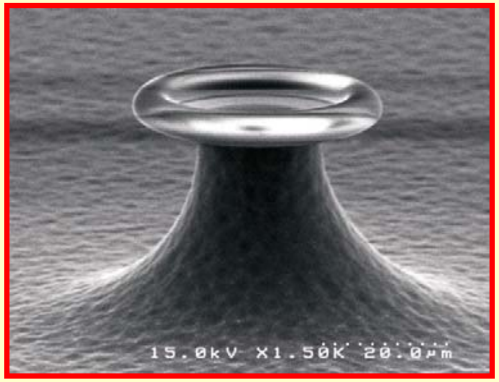
In optical microcavities scattering losses are strongly reduced and whispering gallery modes maintain their high quality factor!



Motivation

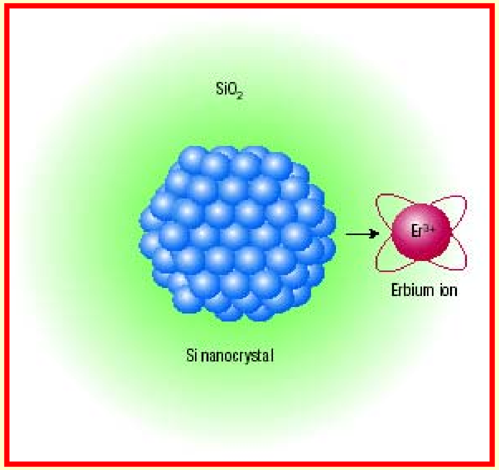
Erbium-doped microcavity laser shown

Polman et al., Appl. Phys. Lett. **84**, 1037 (2004)



Doping of microcavites with nanocrystalline sensitizers (e.g. Si quantum dots and erbium)

- white light pumped infrared light source
  - pumped with white light (via Si bandgap)
  - more efficient pumping (larger absorption cross section)



- reduced cavity Q-factor due to sensitizers
  - infrared absorption losses?
  - increased scattering losses?

Light scattering in a microcavity

Cavity with only absorption

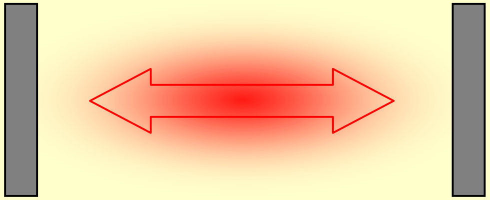
$$Q = \omega\tau$$

$$\boxed{\tau^{-1} = \tau_{abs}^{-1}}$$

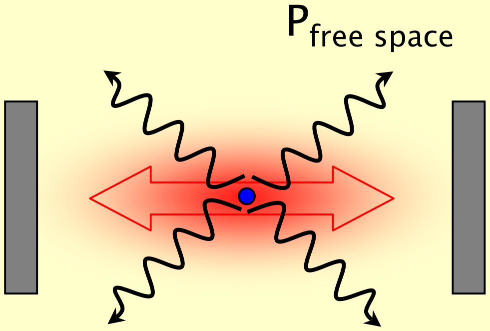
Cavity with absorption and scattering

$$\eta = \frac{P_{cavity}}{P_{cavity} + P_{free\ space}}$$ capture efficiency

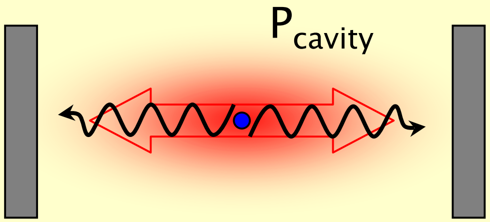
$$\boxed{\tau^{-1} = \tau_{abs}^{-1} + (1-\eta)\gamma_{tot}^{-1}}$$



cavity → absorption



cavity → free space scattering (losses)



cavity → cavity scattering (self coupling)

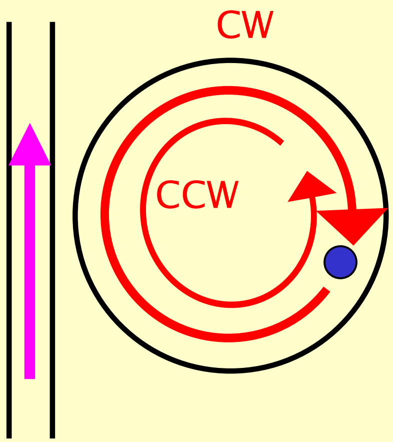
Mode splitting by light scattering

Scattering leads to intermodal coupling

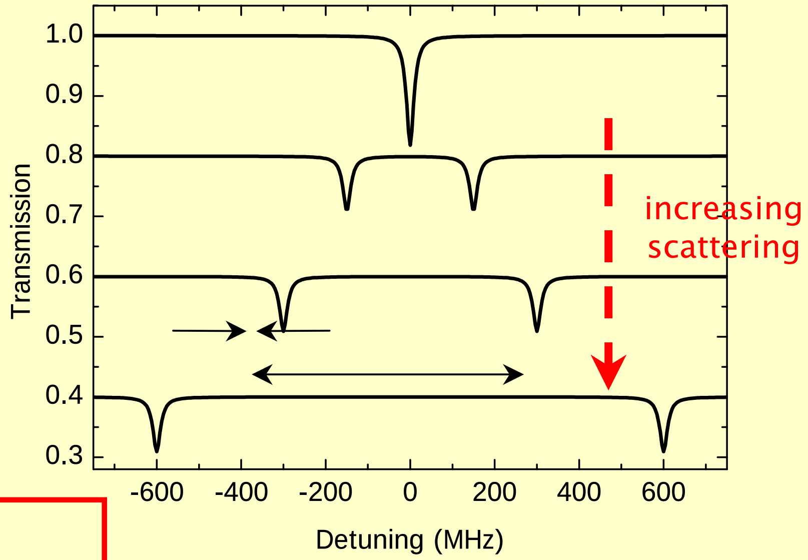
T. J. Kippenberg et al., Optics Letters **27**, 1669 (2002)

$$\frac{d}{dt}a_{CW} = i\Delta\omega\, a_{CW} - \left(\frac{1}{2\tau_0}+\frac{1}{2\tau_e}\right)a_{CW} + \frac{1}{2\gamma_{12}}a_{CCW} + \frac{1}{\sqrt{\tau_e}}s$$

$$\frac{d}{dt}a_{CCW} = i\Delta\omega\, a_{CCW} - \left(\frac{1}{2\tau_0}+\frac{1}{2\tau_e}\right)a_{CCW} + \frac{1}{2\gamma_{21}}a_{CW}$$



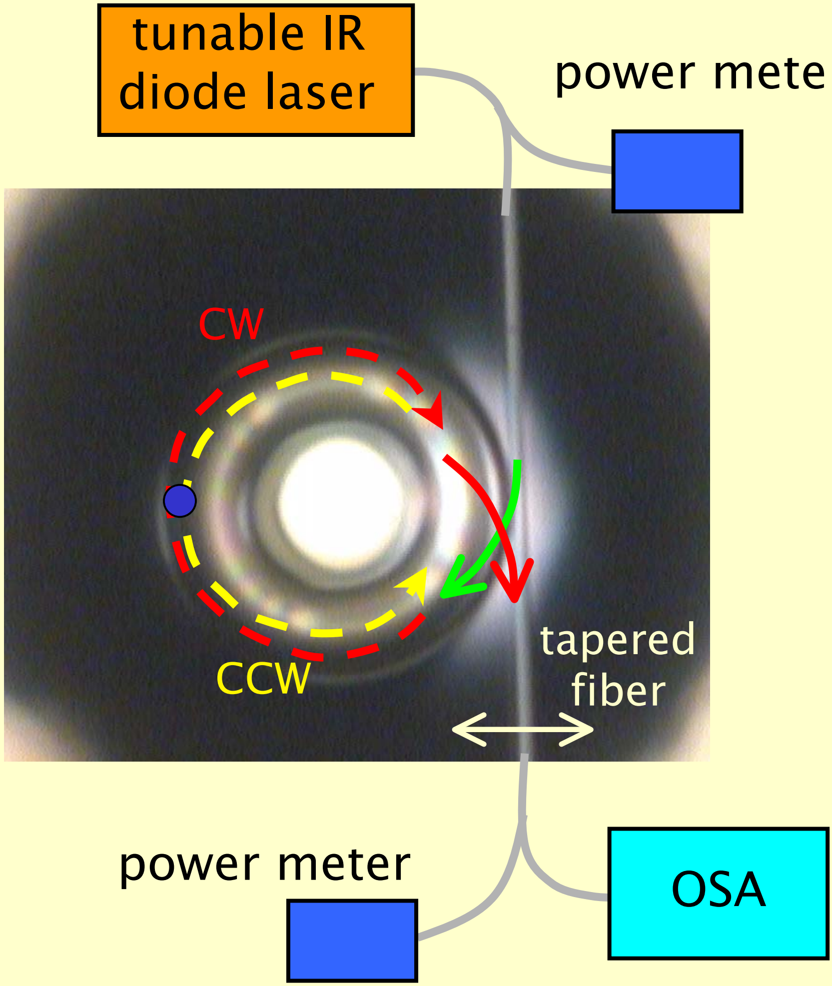
- Steady state solution results in lifting of degeneracy between CW and CCW
- Two modes around ω_0 split with $2/\gamma$
- Width of the resonance is $2/\tau$

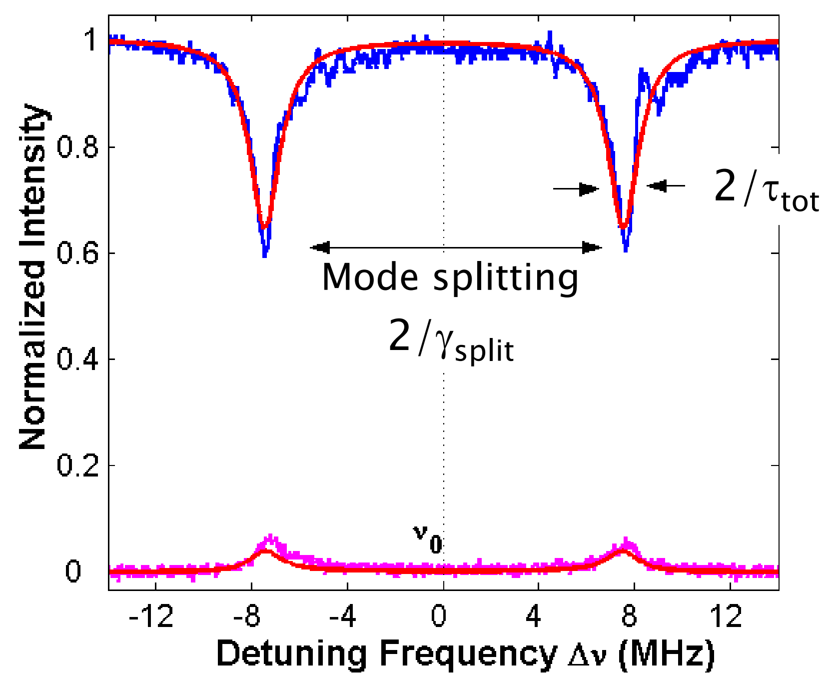


Define splitting visibility

$$\boxed{\Gamma = \frac{splitting\ \ width}{resonance\ \ width} = \frac{\tau_{tot}}{\gamma_{split}} = \frac{0.5\eta\gamma_{tot}^{-1}}{\tau_{abs}^{-1} + (1-\eta)\gamma_{tot}^{-1}}}$$

Measuring Γ

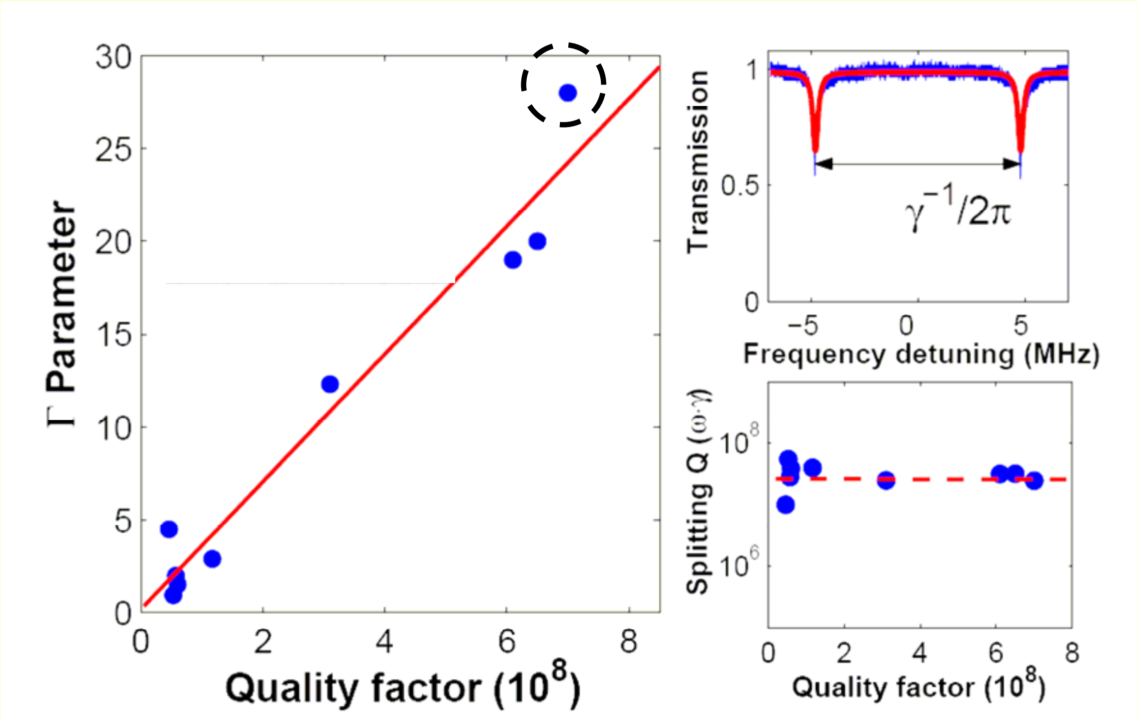




Fit with mode coupling theory
gives γ_{split} and τ_{tot} → splitting visibility Γ

$$\boxed{\Gamma = \frac{\gamma_{split}^{-1}}{\tau_{tot}^{-1}} = \frac{1/2\eta\gamma_{tot}^{-1}}{\tau_{abs}^{-1} + (1-\eta)\gamma_{tot}^{-1}}}$$

Scattering in a single undoped microtoroid



Γ=29 with Q=5×10⁸
51 MHz scattering events
with only 2 MHz loss

$$\Gamma = \frac{\tau}{\gamma} = \left(\frac{\frac{1}{2}\eta\gamma_{tot}^{-1}}{\tau_0^{-1} + (1-\eta)\gamma_{tot}^{-1}} \right)$$

If absorption limited $(\tau_0^{-1} >> (1-\eta)\gamma^{-1})$

① $$\Gamma = \frac{\eta Q}{2\gamma_{tot}\omega}$$ Linear increase with Q

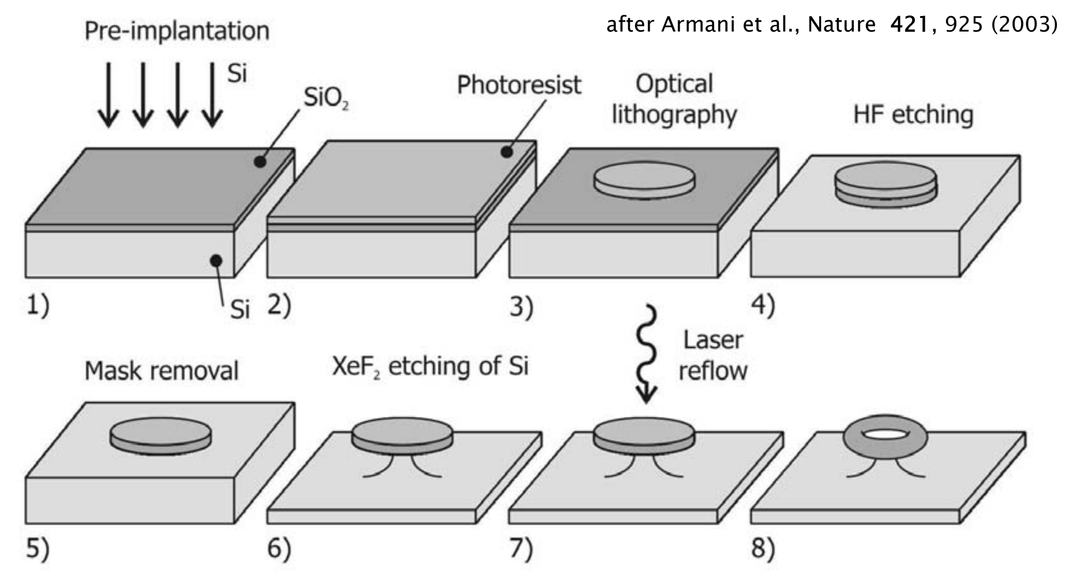
② With highest point scattering limited (Γ=30) $$\eta > \frac{2\Gamma}{2\Gamma+1}$$

→ lower limit on $\eta > 97$ %

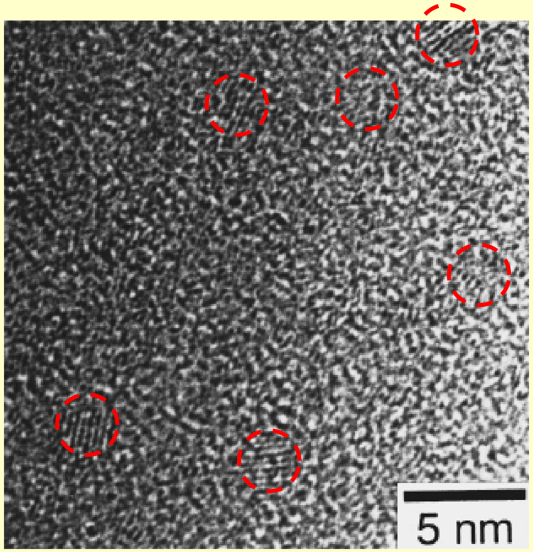
Fabrication of Si quantum dot doped microtoroids

Si implantation in SiO_2 to create supersaturated solution
3 at.% excess Si (900 keV, $9.1 \cdot 10^{16}$ Si/cm^2)

Thermal annealing
10 min. at 1100 °C, Si diffusion → nucleation of aggregates
30 min. at 800 °C, forming gas, Hydrogen passivation of surface defects → optically active Si quantum dots



after Armani et al., Nature **421**, 925 (2003)



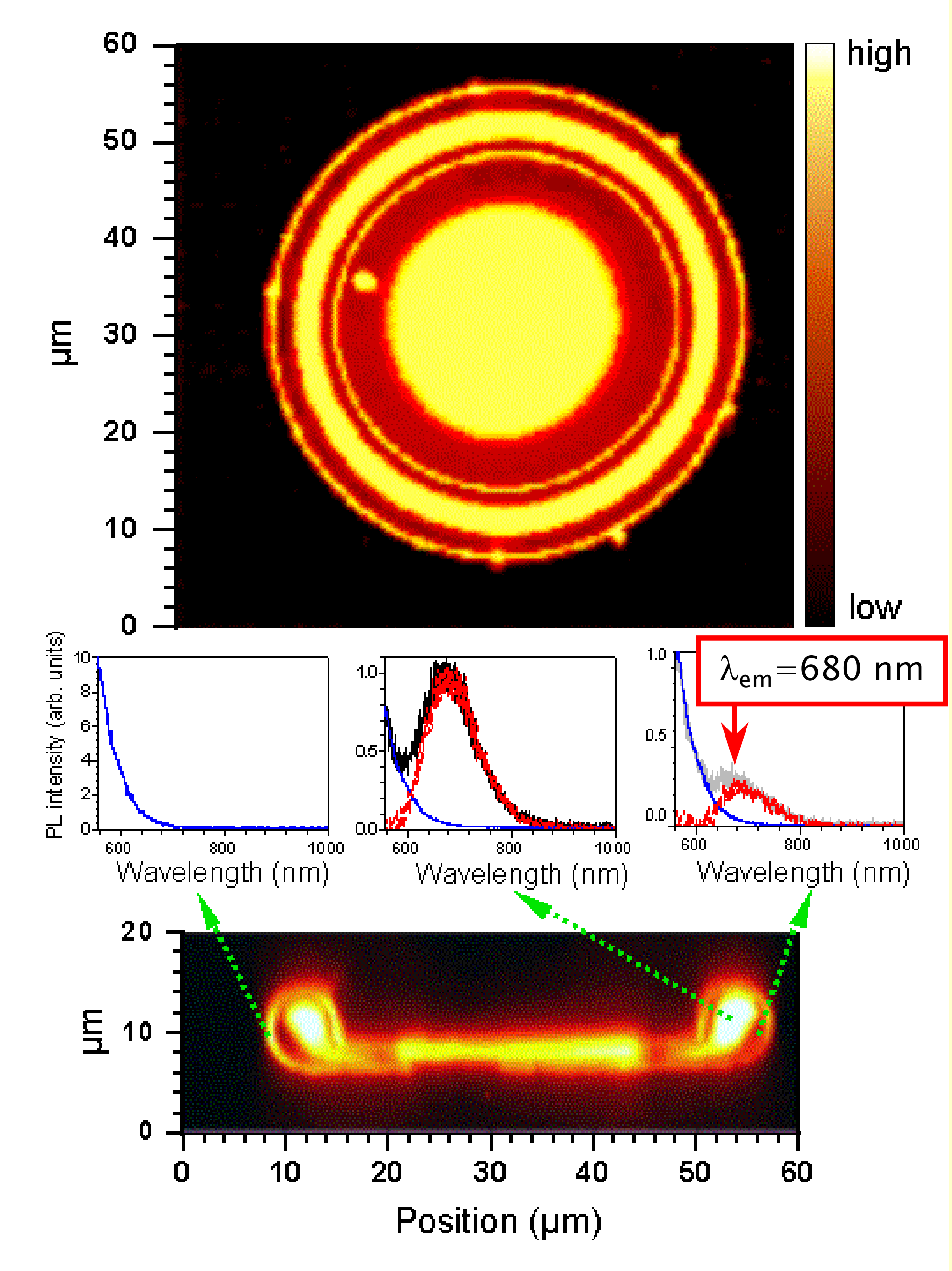
Min et al. Appl. Phys. Lett. **69**, 2033 (1996)

Characterization of Si QD doped microtoroids

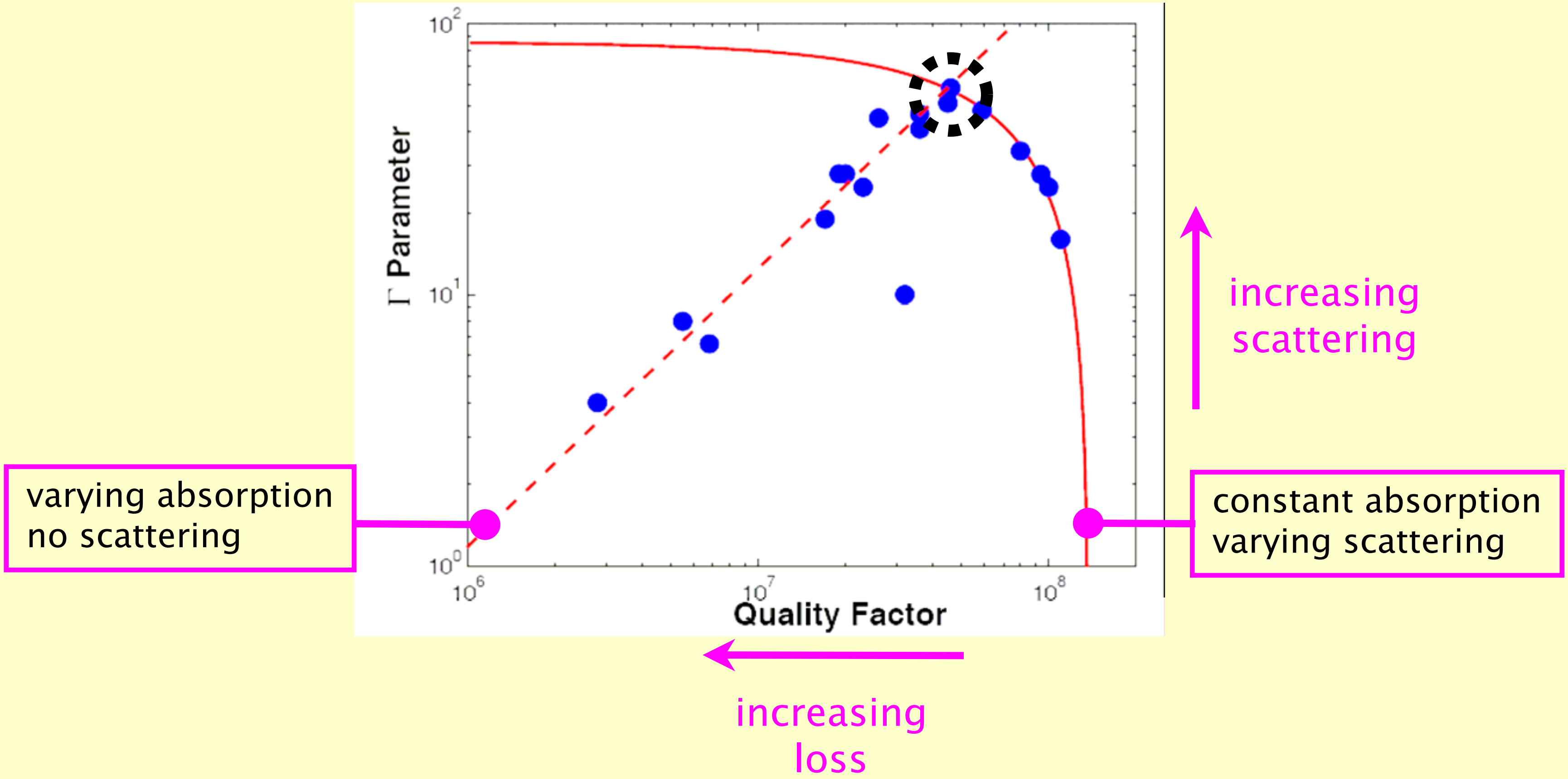
- Confocal microscopy imaging $\lambda_{exc}=532$ nm
- Index matching with oil (n=1.52), 100× plan apochromatic objective
- Rhodamine dissolved in solution ($\lambda_{em}=545$ nm) to image toroidal perimeter

At toroidal perimeter $\lambda_{em}=680$ nm
$\rightarrow$ radius 1.6 nm
Wolkin et al., Phys. Rev. Lett. **82**, 197 (1999)

Infrared scattering on Si QDs in SiO_2
$n_{Si}=3.45$, $n_{SiO2}=1.45$, $\lambda=1550$ nm
$\rightarrow \sigma_{scatt}=1\cdot10^{-25}$ cm^2



Scattering in a single Si-QD-doped microtoroid



varying absorption
no scattering

constant absorption
varying scattering

increasing
scattering

increasing
loss

- Cavities maintain their high Q
- Much stronger scattering than in undoped microtoroids ($\Gamma_{max}=60$)
- Scattering losses and absorption become comparable
- Fit with varying scattering and fixed absorption
  $Q_0=2\times10^8$ ($\tau_0=115$ ns), $\eta=99.4$ %

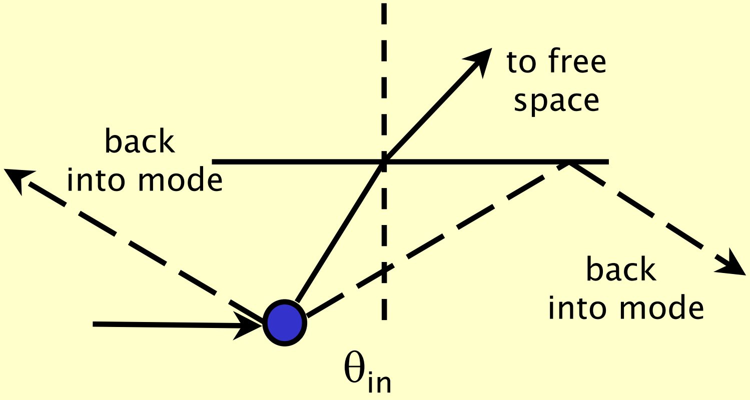
Theoretical analysis

① **Geometrical model, critical angle**

$$\sin\theta > \frac{1}{n_{12}}$$

$\eta_{TM} = 89\ \%$ $\eta_{TE} = 64\ \%$ Too low...

Gorodetsky et al., J. Opt. Soc. Am. B 17, 1051 (2000)



② **Purcell enhanced capture efficiency**

$$F = \frac{3}{4\pi^2}\frac{Q}{V}\left(\frac{\lambda}{n}\right)^3 = \frac{\rho_{cavity}}{\rho_{free-space}} = \frac{\gamma^{-1}_{cavity}}{\gamma^{-1}_{free-space}}$$

$$\eta = \frac{F(Q)}{F(Q)+1}$$

Different analysis (capture efficiency depends on Q)

Splitting rate depends on Q Not found...

③ **Coupled mode theory**

$$\gamma^{-1} = \frac{1}{\sqrt{V_{eff}}}$$

Splitting depends not on Q

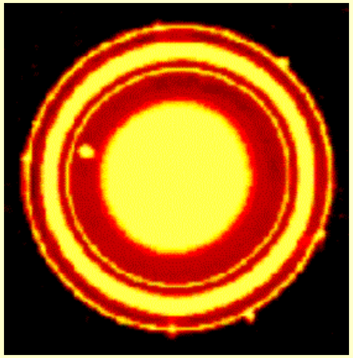
Stronger scattering in smaller cavities

Found!

Gorodetsky et al., J. Opt. Soc. Am. B 17, 1051 (2000)

Further experiments needed to pinpoint the exact model.

Summary



✓ Succesfully doped high-Q microtoroids with Si quantum dot light scatterers

✓ Shown a new technique to measure the light scattering efficiency in microcavities

✓ Determined the scattering efficiency and absorption related Q of a single microtoroid $\eta = 99.4\ \%$, $Q_0 = 2 \times 10^8$

✓ Analysis shows the possibility to compare various theories for scattering in microcavities