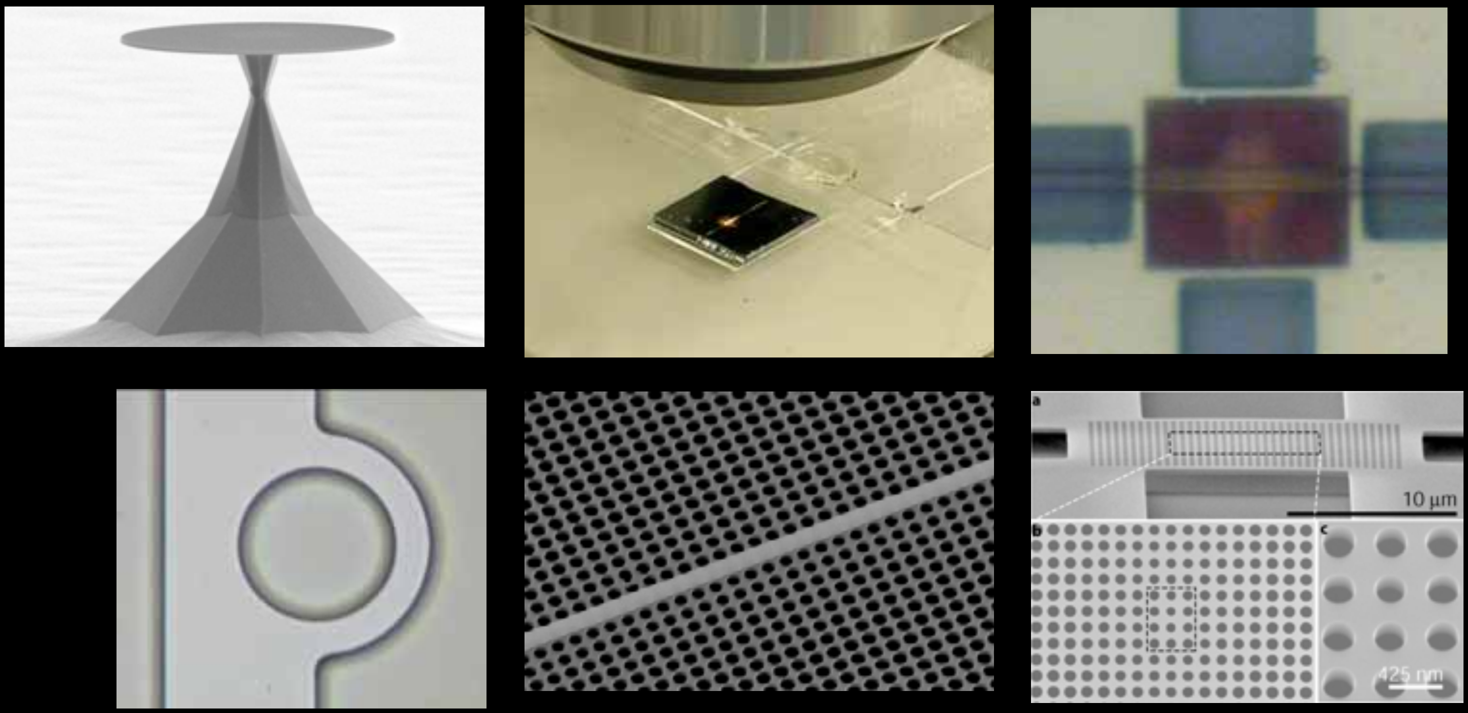
Nonlinear dynamics in Si micro- and nano-photonic systems



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Outline

- Some basics…geometry and physics of nano-optic structures
- Hopf-bifurcation and self-oscillation in SOI microdisk resonators
- Some trends and numbers in nanophotonics
- CDS 273 topics

Collaborators:

- **Matt Borselli, Tom Johnson, Paul Barclay**
- Hideo Mabuchi and Ben Lev

Scaling with Q and V_{eff}

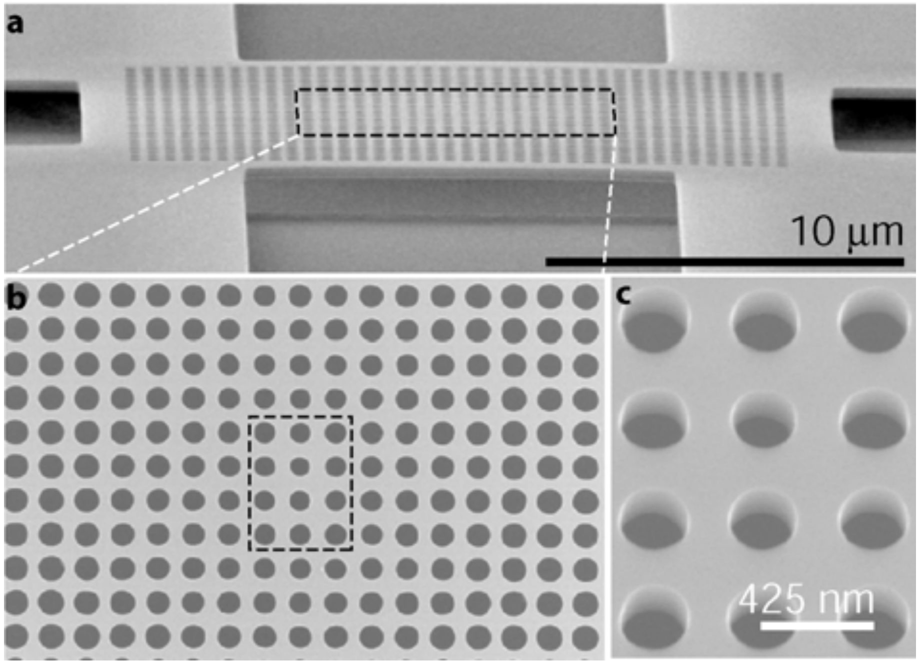
- The interaction of matter with light can be dramatically altered by the presence of a microcavity.

- The degree to which it is affected is a function of the spectral (photon lifetime, $Q=\omega\tau_{ph}$) and the spatial (electric field energy density of the field, V_{eff}) density within the cavity.

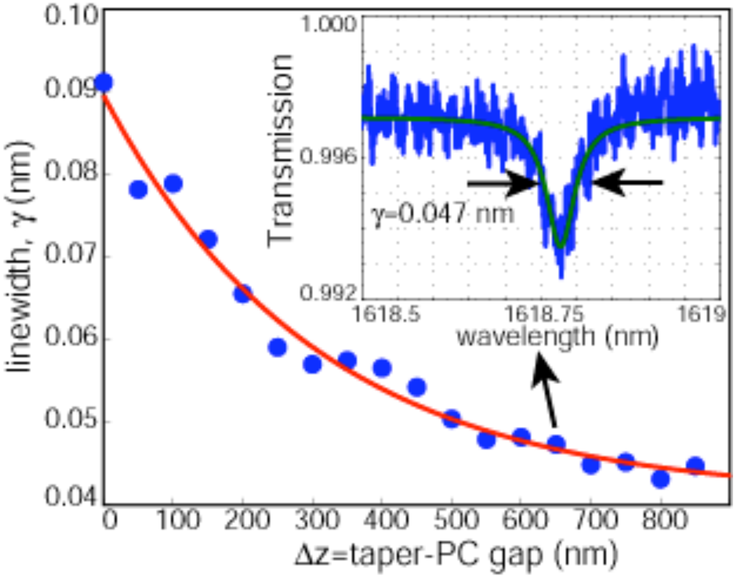
- A wide range of optical processes depending on Q and Veff include:
  - Spontaneous emission control (Purcell factor ~ Q/V_{eff})
  - Strong matter-photon coupling in cavity QED (~ $(Q/V_{eff})^{1/2}$)
  - Non-linear thresholds (Raman laser ~ $V_{nl,eff}/Q^2$)
  - Biomolecular sensing (abs. or phase spectroscopy ~ Q/V_{eff})

Geometry at the wavelength and sub-wavelength scale can also play an important role through dispersive effects

Photonic Crystal Devices



- Cavities fabricated in undercut silicon membranes
- Linewidth of cavity mode (γ) examined as a function of taper position above the PC; can back out an unloaded cavity Q factor
- FDTD simulations of structure with appropriate hole sizes predict Q~56,000 and V_{eff}~$0.88(\lambda/n)^3$



Data fit to curve $\gamma = \gamma_o + \beta^*\exp(-\Delta/\alpha)$

measured linewidth

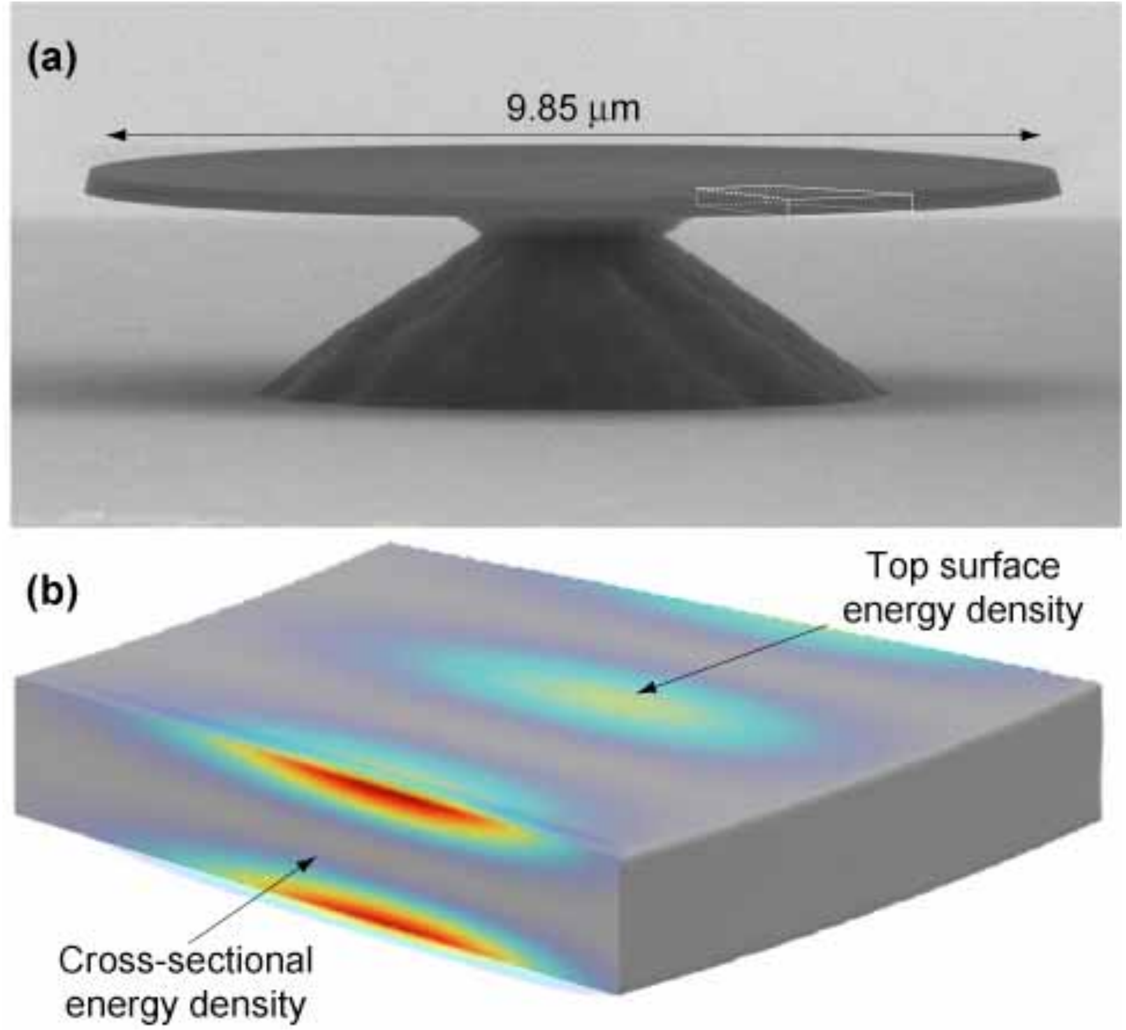
unloaded linewidth

$\gamma_o \sim 0.041$ nm

$Q=\lambda_o/\gamma_o \sim 39{,}500$

***K. Srinivasan, et al., PRB Rapids, 2004 (http://arxiv.org/quant-ph/abs/0309190).**

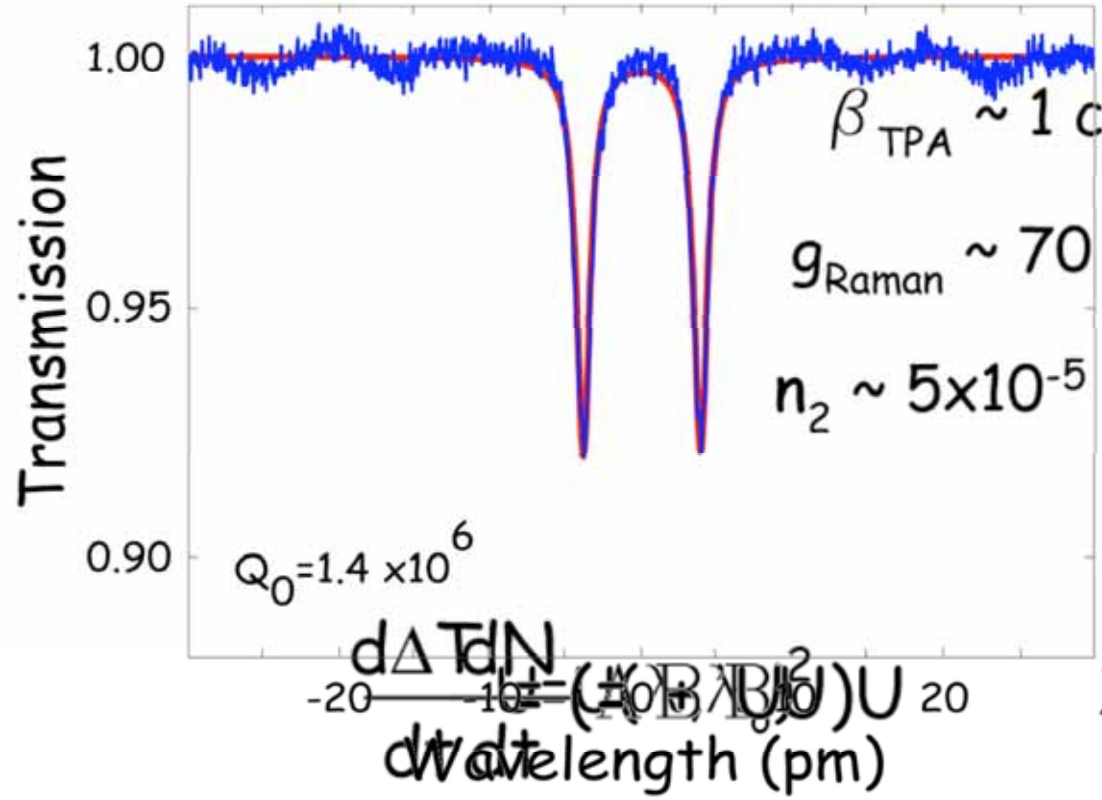
Si “microdisk” optical resonators



- thin SOI, 215 nm thick
- TM mode has large field strength at the top and bottom Si-air interfaces
- Approx. 30% of electric field energy density lies in the cladding (with silica clad) → designed for Er-doped silica clad SOI microlaser work
- $Q = 5\text{x}10^6$, $V_{eff} = 10\ (\lambda/n)^3$

Nonlinear optics in Si resonators

$$I = \frac{Q_i}{V_{eff}} \frac{P_{in}}{\omega_o} \frac{c}{n_g} \sim 1\ GW/cm^2$$



$\beta_{TPA} \sim 1\ cm/GW$

$g_{Raman} \sim 70\ cm/GW$

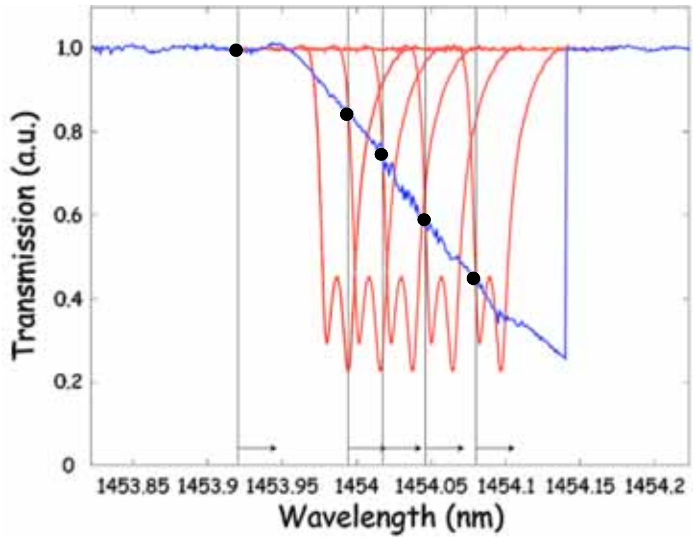
$n_2 \sim 5x10^{-5}\ cm^2/GW$

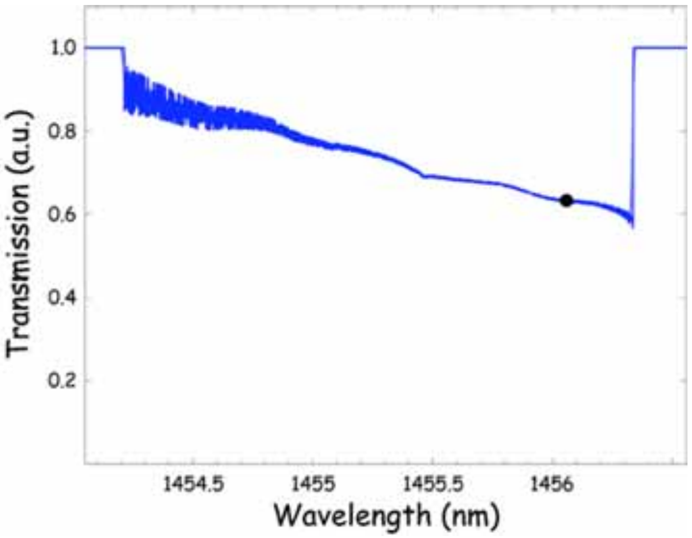
$\frac{d\Delta T}{dt} = ($[illegible]$)U$

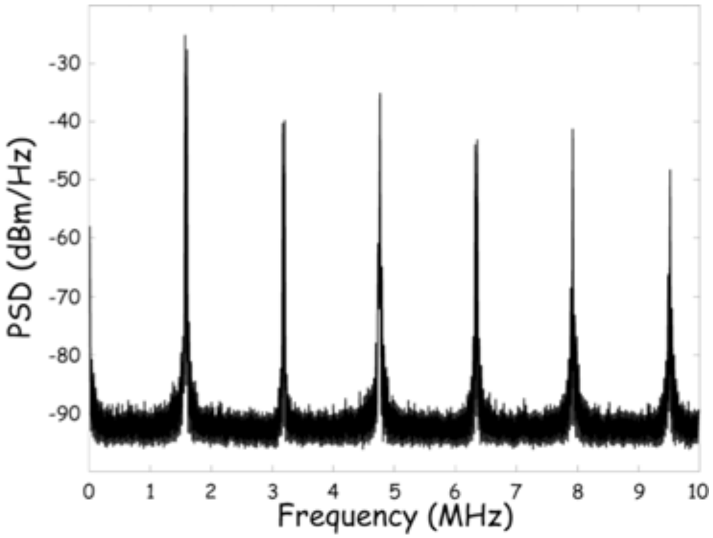
$\frac{dN}{dt} = ($[illegible]$)U^2$

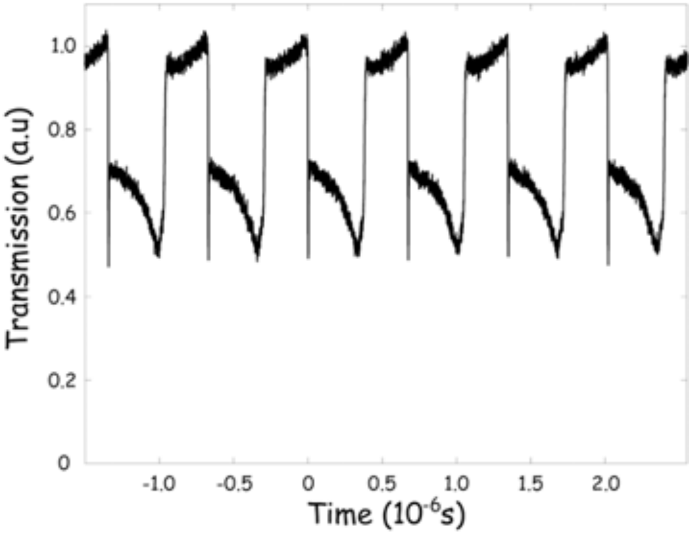
$\lambda_o = \lambda_o(N, \Delta T)$

Thermo-optical bistability and self-oscillation

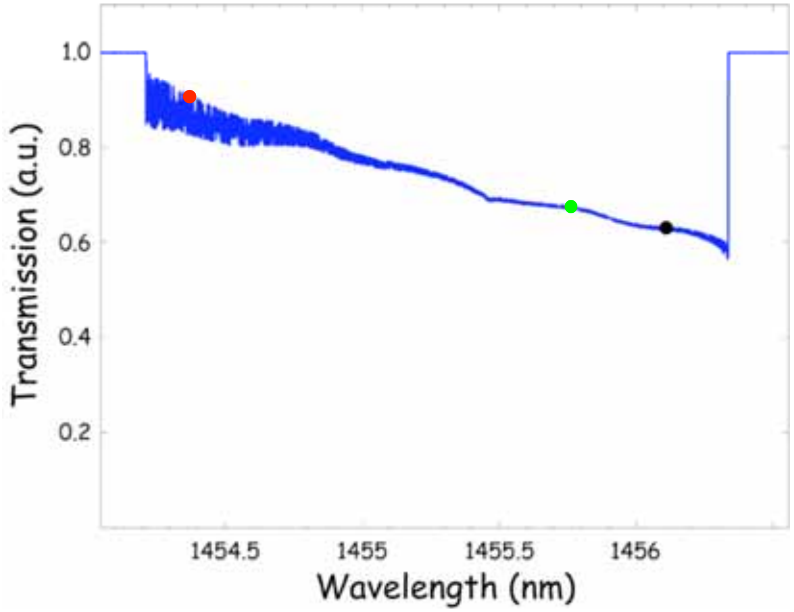


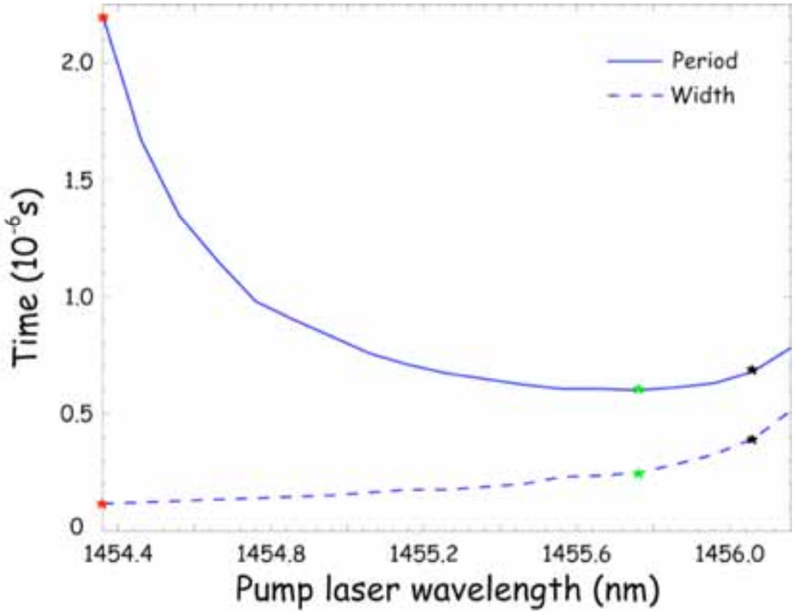


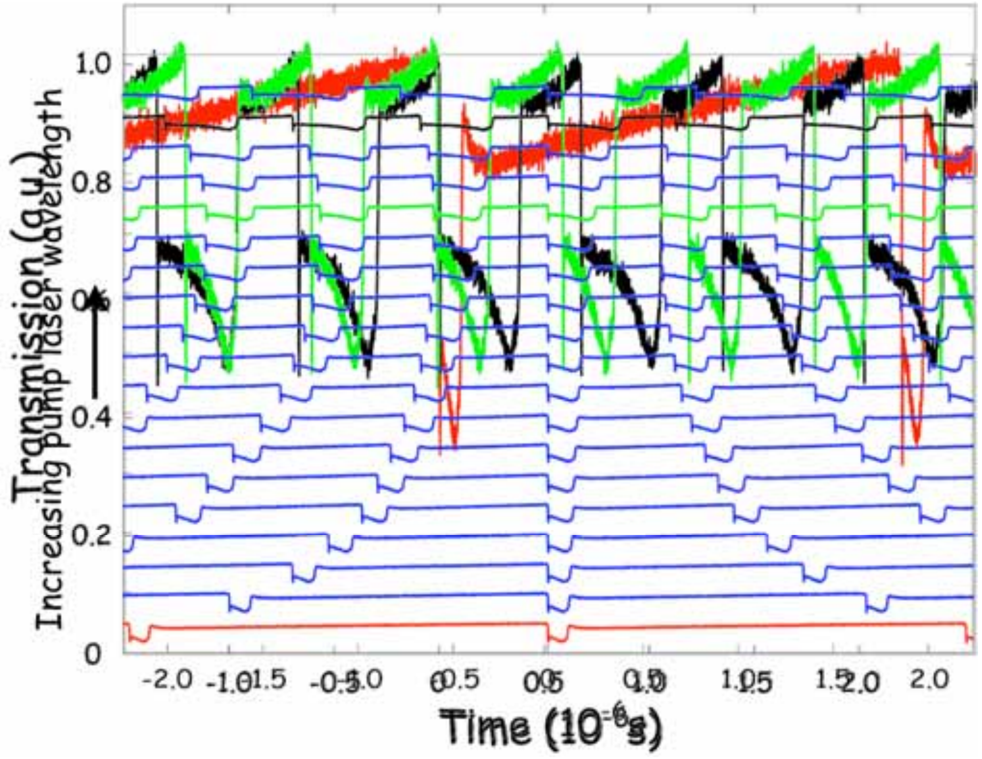




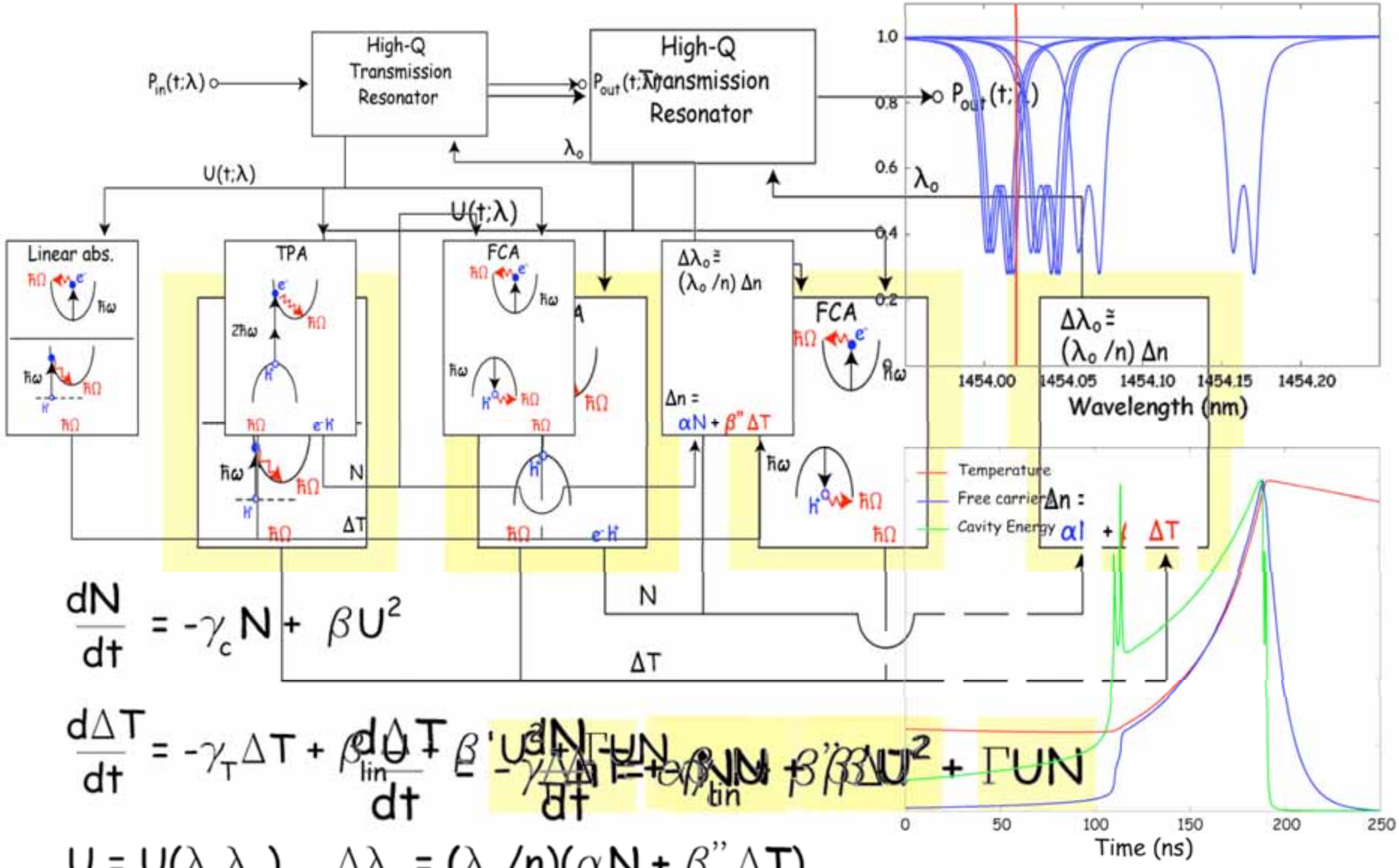
Self-oscillation: pump wavelength dependence







Self-oscillations: a simple model

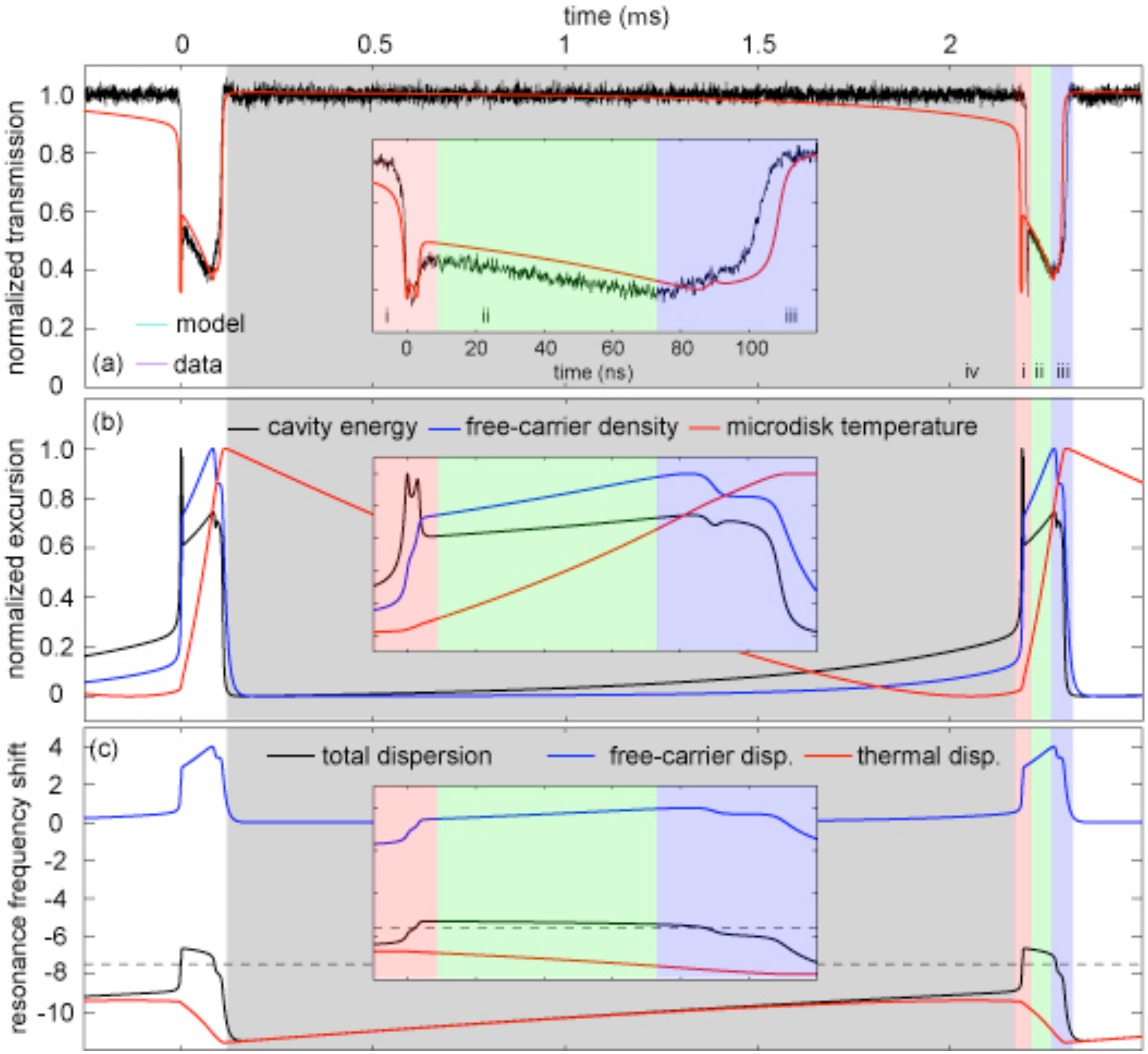


$$\frac{dN}{dt} = -\gamma_c N + \beta U^2$$

$$\frac{d\Delta T}{dt} = -\gamma_T \Delta T + \beta_{lin} U + \beta' U^2 + \Gamma U N$$

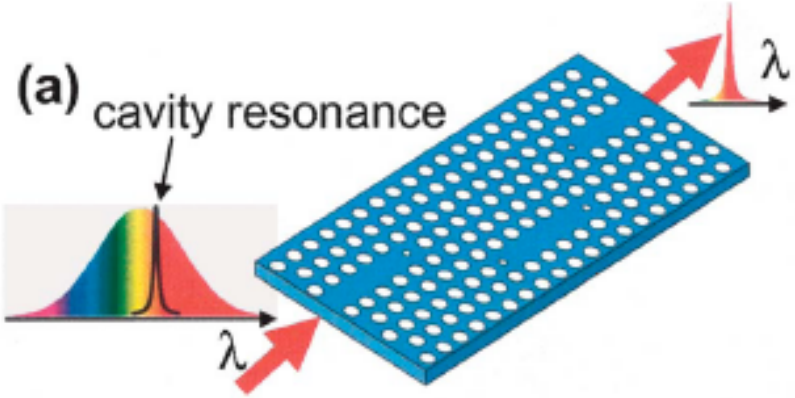
$$U = U(\lambda,\lambda_o) \qquad \Delta\lambda_o = (\lambda_o/n)(\alpha N + \beta'' \Delta T)$$

Comparison: model and experiment

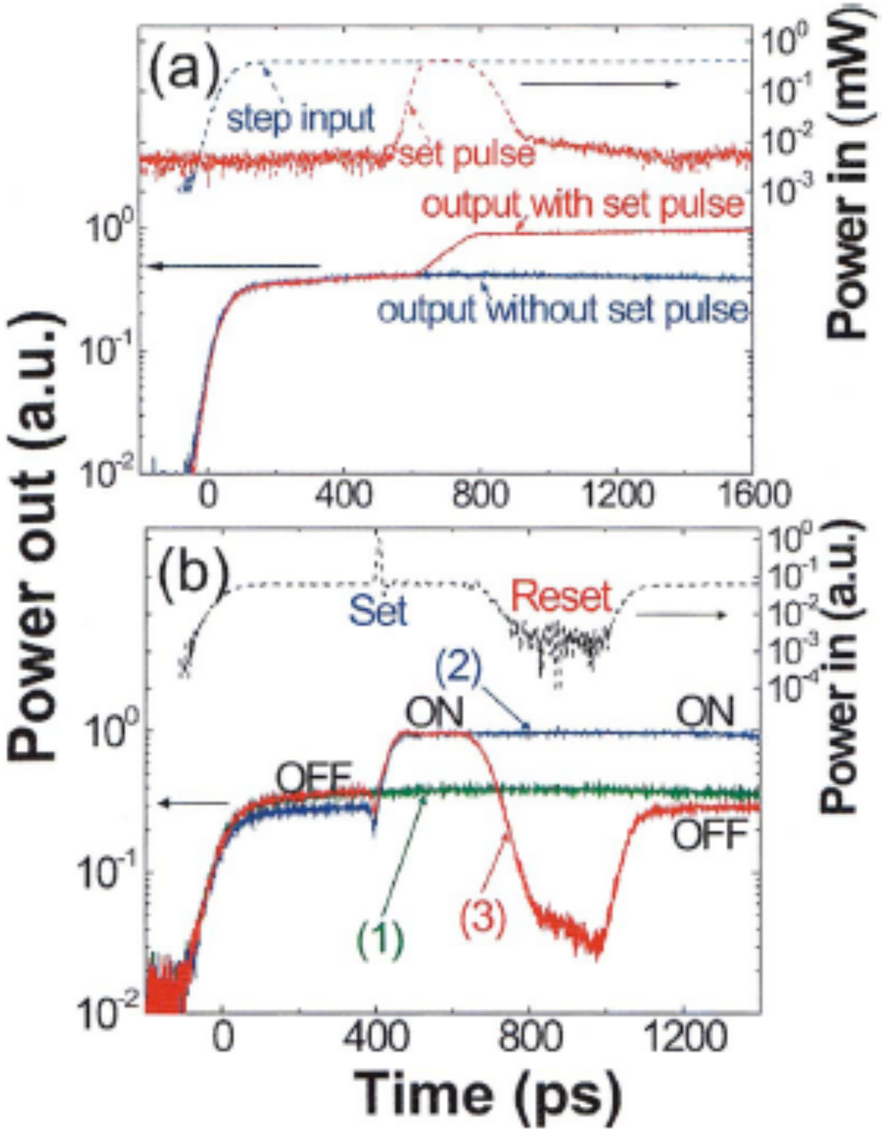


Fast bi-stable optical memory

*Takasumi Tanabe, et al., Optics Letters, v30(19), Oct. 2005



- Fast switching, < 80 ps due to fast surface recombination of free-carriers
- Low input power (< 400 μW) and switching energy (74 fJ)
- Internal cavity energy for switching < 5 fJ or approx. 10^4 photons



Some numbers

1. Free-carrier dispersion is proportional to free-carrier density ($\delta n = (-1.73\mathrm{x}10^{-19}\ \mathrm{cm}^3)n_{fc}$), which in turn is set by the TPA rate ~ $(U/V)^2$
2. The required dispersion for bistability scales as $1/Q$
3. This implies that $U_{th.} \sim V/Q^{1/2}$, and $P_{i,th.} \sim V/Q^{3/2}$

If one were to fabricate a Si photonic crystal nanocavity with:

a. mode volume ~ $1\ (\lambda/n)^3 \sim 0.1\ \mu\mathrm{m}^3$ [current size],

b. Q ~ 10^7 [lightly doped Si material limit],

then the threshold for optical (free-carrier driven) bistability would be,

$U_{th.} \sim 100$ aJ (10^3 photons) or $P_{i,th}. \sim 10$ nW

$N_{fc,th.} \sim (V/Q)(n)/(1.73\mathrm{x}10^{-19}\ \mathrm{cm}^3) \sim 1/4$!

CDS 273 topics

- Modern fabrication techniques and materials have evolved significantly over the last decade

- Current nanophotonic structures which can be made quite simply in the lab today have nonlinearities much stronger than in previous optical systems, and in many cases display nonlinearities not even considered in prior work

- There is currently a need to reassess the nonlinear properties of these modern optical devices, and an opportunity to develop new architectures and methods for communication and computation based upon nonlinear control theory

- Finally, as alluded to in the above simple calculation, current devices are fast approaching the few quanta level (both in photons and electrons), and schemes to exploit and/or deal with quantum noise fluctuations are also likely to be necessary

[redacted]