# Superradiance for Atoms Trapped along a Photonic Crystal Waveguide

160614

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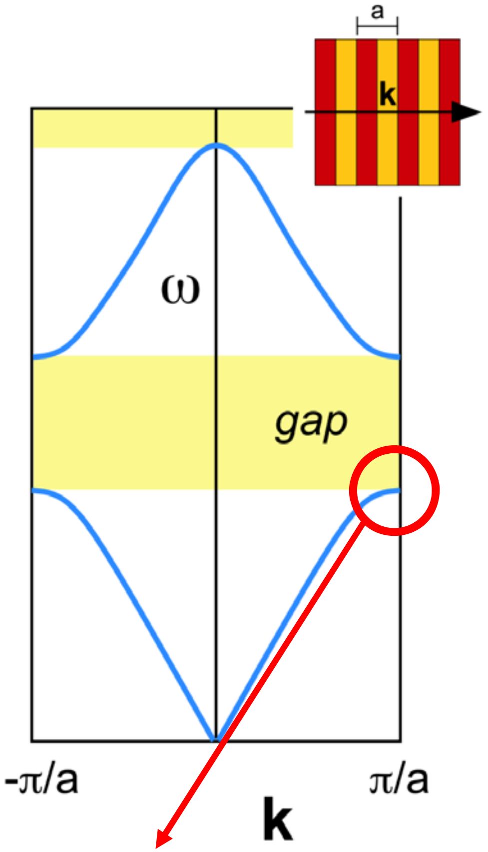
- Prof. at California Institute of Technology(Caltech)
- Recent research subject
  - ➢ Atom-field interactions in photonic crystals
  - ➢ Atom-atom interactions in photonic crystals

Recent Publication list (2012/7~2016/6)

- Atom-atom interactions around the band edge of a photonic crystal waveguide.
- Superradiance for atoms trapped along a photonic crystal waveguide.
- Subwavelength vacuum lattices and atom-atom interactions in two-dimensional photonic crystals.
- Quantum many-body models with cold atoms coupled to photonic crystals.
- Atom–light interactions in photonic crystals.
- Nanowire photonic crystal waveguides for single-atom trapping and strong light-matter interactions.
- Trapped atoms in one-dimensional photonic crystals.
- Self-Organization of Atoms along a Nanophotonic Waveguide.
- Demonstration of a State-Insensitive, Compensated Nanofiber Trap.

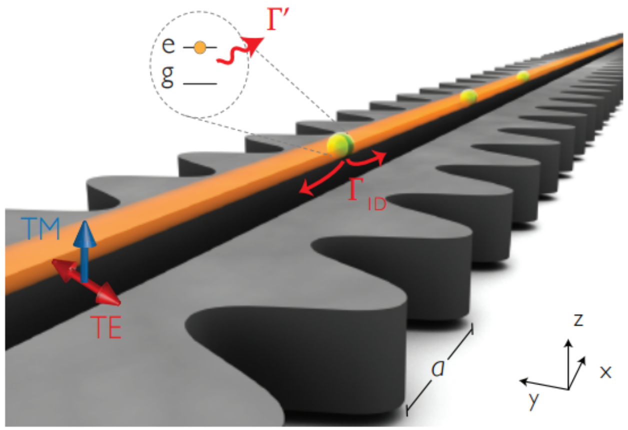
# Introduction

## Photonic band gap

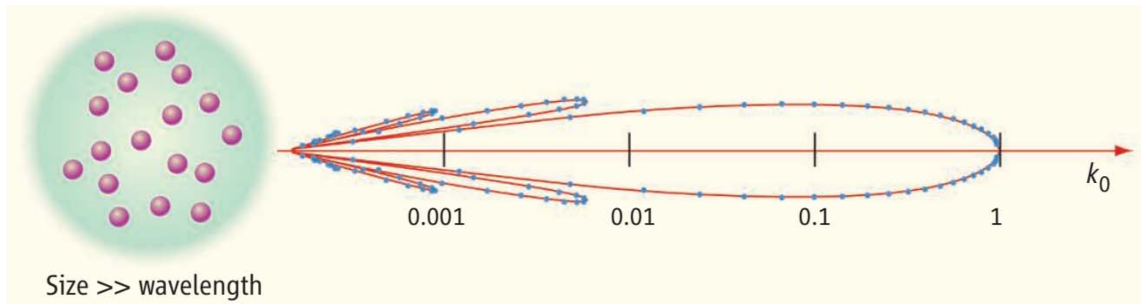



Group velocity slows down near the edge.

## Enhancement of atom-field interaction




## Single photon superradiance





The Super of Superradiance
Atom-atom interactions around the band edge of a photonic crystal waveguide
Introduction to Photonic Crystals: Bloch's Theorem, Band Diagrams, and Gaps (But No Defects)

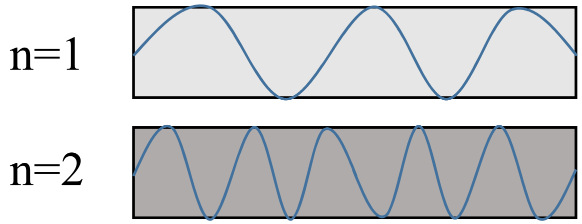
# Spontaneous emission rate in dielectric medium

Hamiltonian of the field is

$$\mathrm{H} = \frac{1}{2}\int dV(\varepsilon \boldsymbol{E}\cdot\boldsymbol{E} + \mu^{-1}\boldsymbol{B}\cdot\boldsymbol{B})$$

Factor $\varepsilon$ leads to the different electric field,

$$\widehat{\boldsymbol{E}} = \frac{1}{n}\widehat{\boldsymbol{E}}_{free}$$




Density of the modes is

$$k^2 dk = \frac{n^3}{c^3}\omega^2 d\omega$$

From Fermi's golden rule, spontaneous emission rate is

$$\Gamma \propto \int k^2 dk \langle 0|\widehat{\boldsymbol{E}}_j^{\dagger}(k)\widehat{\boldsymbol{E}}_j(k)|0\rangle \delta(\omega_k - \omega_0)$$

The result is

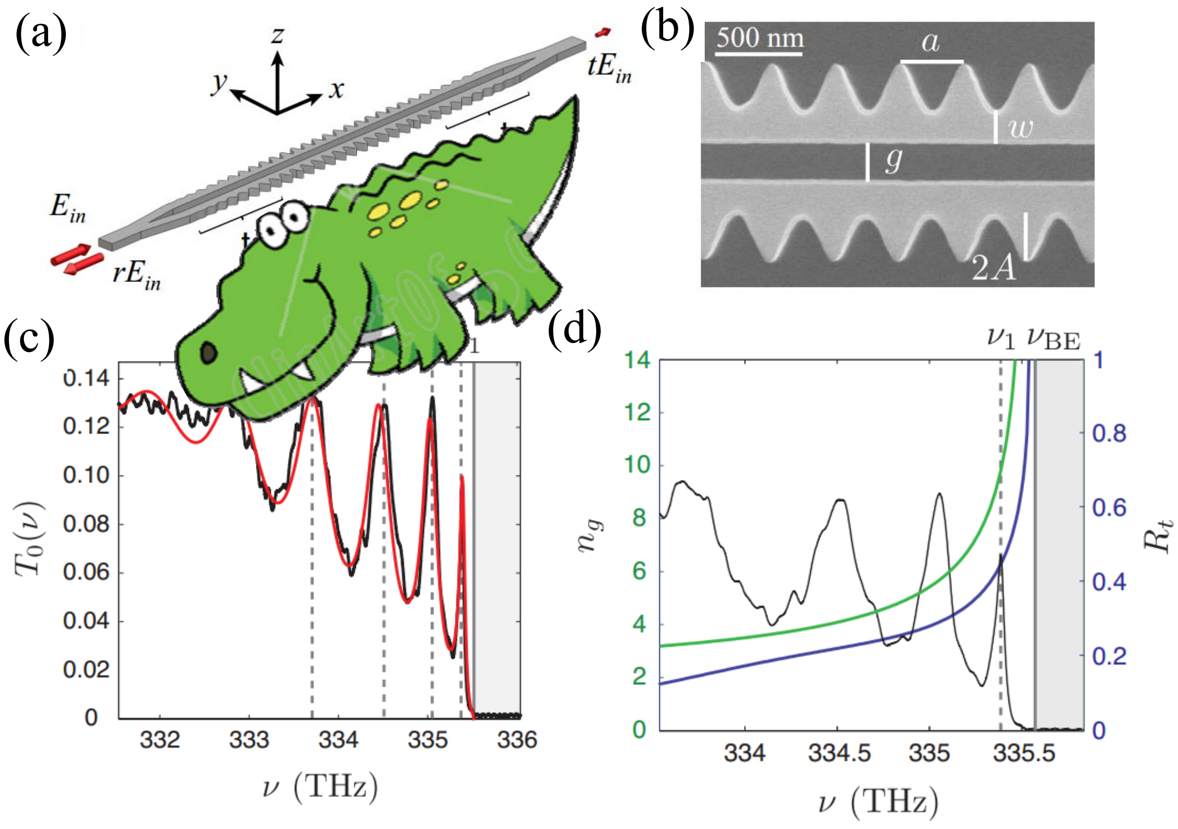
$$\Gamma = \frac{n^3}{n^2}\Gamma_0 = \mathrm{n}\Gamma_0$$

Note. some modifications due to local field correction factors yield,

$$\Gamma = \left(\frac{3\mathrm{n}^2}{2n^2+1}\right)^2 \mathrm{n}\Gamma_0$$

Decay of excited atoms in absorbing dielectrics, J. Phys. B **29** (1996) 3763–3781

# Alligator photonic crystal waveguide (APCW)

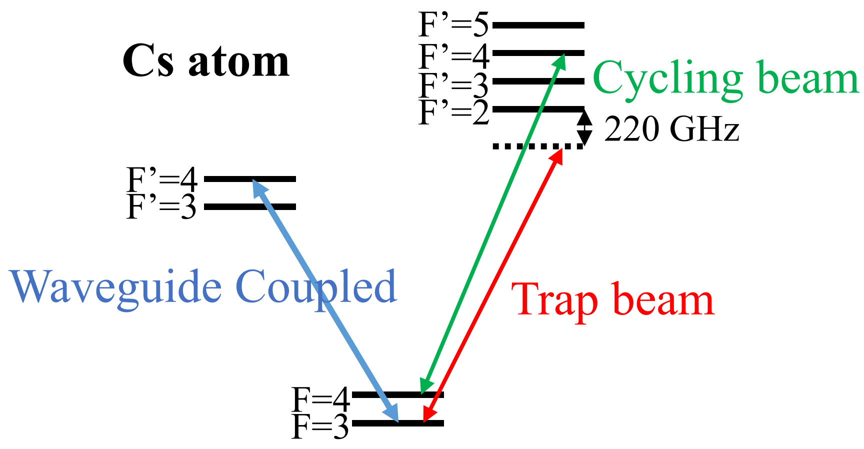



(a) Alligator photonic crystal waveguide
(b) SEM image
(c) Measured(black) and fitted(red) transmission spectrum
(d) Estimated group index $n_g$ (green) and taper reflection $R_t$ (blue)

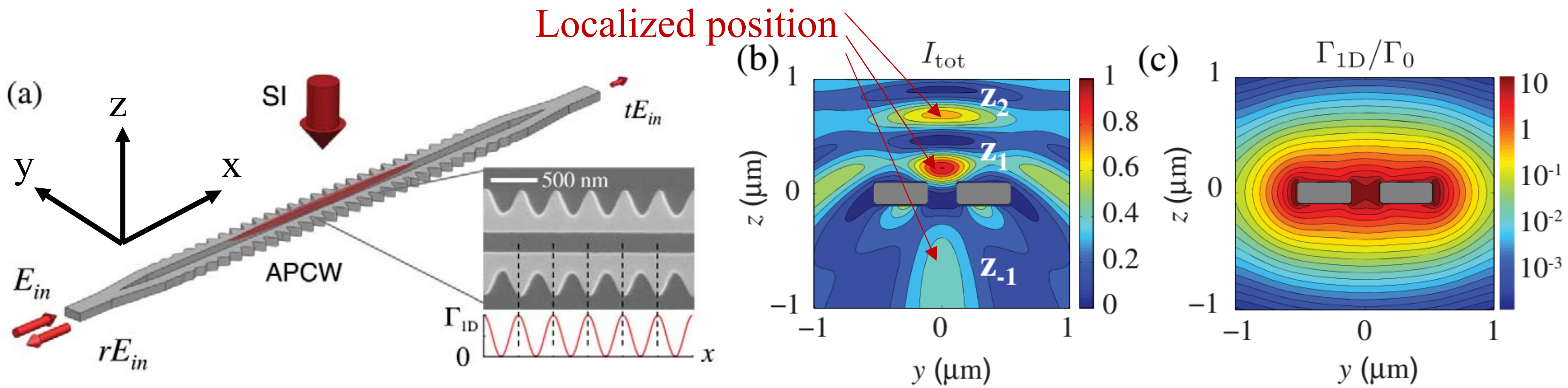
We stress "waveguide" and not "cavity" QED because the dominant effects in our experiment are a result of the combination of atom-light localization and an enhancement in the atom-field coupling due to band structure, "slow-light" effect.

- L=55.7 um
- R=0.48
- Linewidth=66 GHz
- $n_g \approx 11$
- $\Gamma_{1D} \sim \Gamma_{vac}$

# Trap method



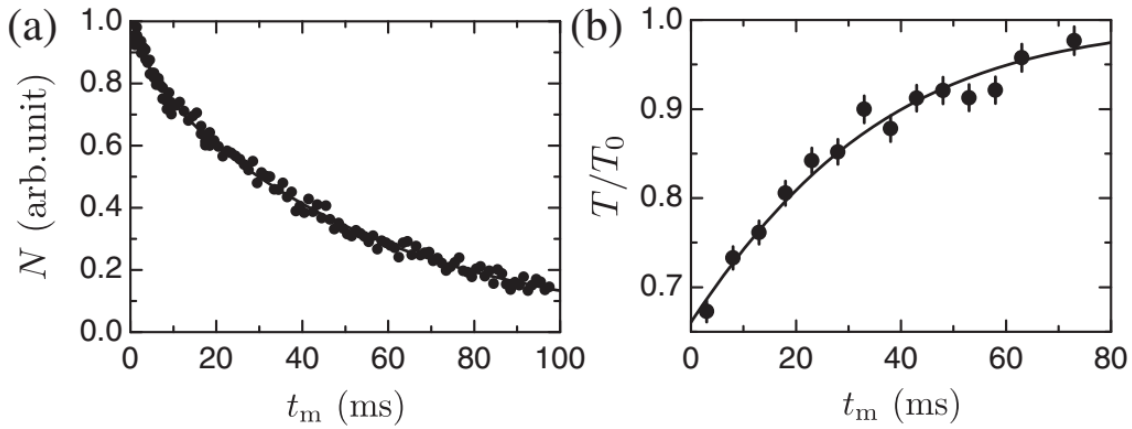

- Optical potentials are made by interference pattern of a side-illumination (SI) beam and its reflection from the surface of the APCW
- Only those atoms sufficiently close to the APCW($Z_1$ site) can interact strongly with guided-mode(GM) photons because of the exponential falloff of the guided mode intensity(fig. c)
- Along the x axis, only those close to the center of a unit cell can strongly couple to the guided mode. ($\Gamma_{1D} \sim \cos^2(kx)$)



# Lifetime of trapped atoms

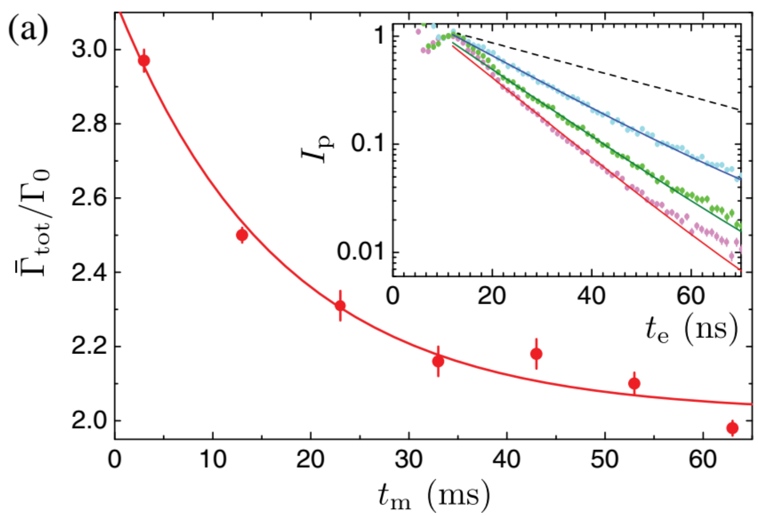

$t_m \equiv t_{hold} + \Delta t_m/2$

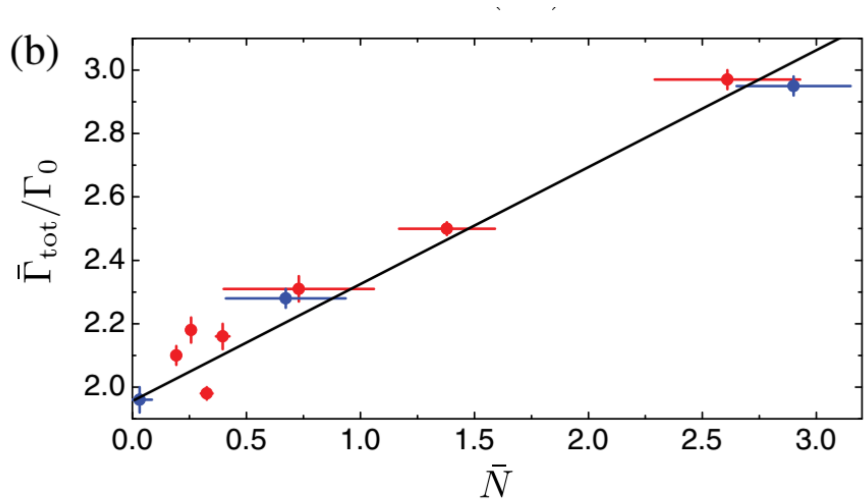
- $t_{hold}$ is used to control average atom number.
- Free space lifetime ($\tau_{fs}$ = 54 ± 5 ms)
  - Free space absorption imaging in $\Delta t_m$(~0.2 ms)
- Guided mode lifetime ($\tau_{GM}$ = 28 ± 2 ms)
  - launch a resonant GM probe and measure transmission in $\Delta t_m$(~5 ms)
- Atom loss is induced by stronger intensity near APCW.



# Decay rate and atom number

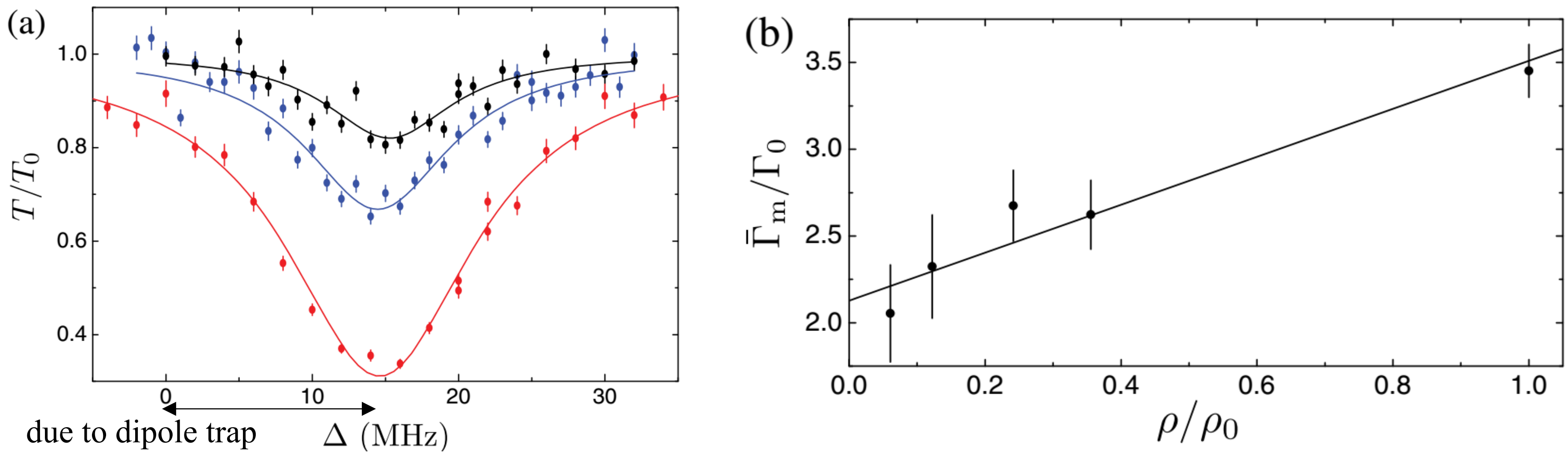
- Short excitation pulses (FWHM 10 ns) with <n> ≪ 1 per pulse
- The excitation cycle is repeated every 500 ns for $\Delta t_m$ =6 ms.
- Numbers of atoms are adjusted by changing $t_{hold}$(Red) and changing MOT loading time(Blue) in figure b.
- Because the atoms are excited by photon <n> ≪ 1, decay rate is proportional to <N>, not $<N>^2$. (Single photon superradiance)



# Line broadening for steady-state transmission spectra

- The measured linewidths $\Gamma_m$ are significantly broader than the free-space width $\Gamma_0/2\pi$=4.56 MHz
- Number of atoms are adjusted by changing MOT loading times.
- $t_{hold}$=0.5 ms and $\Delta t_m$=5ms is used.




$\rho/\rho_0$=0.12, 0.24, 1