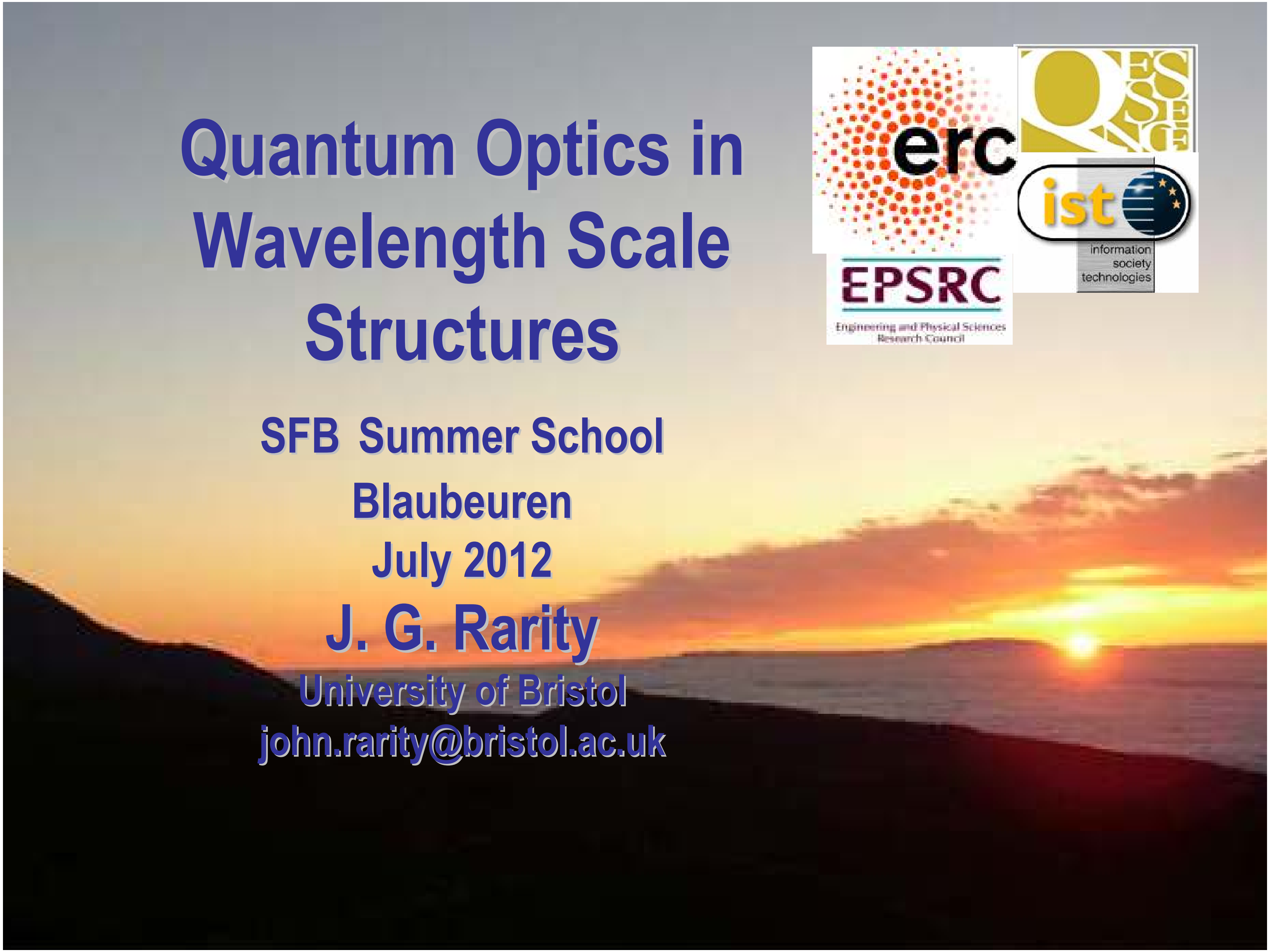
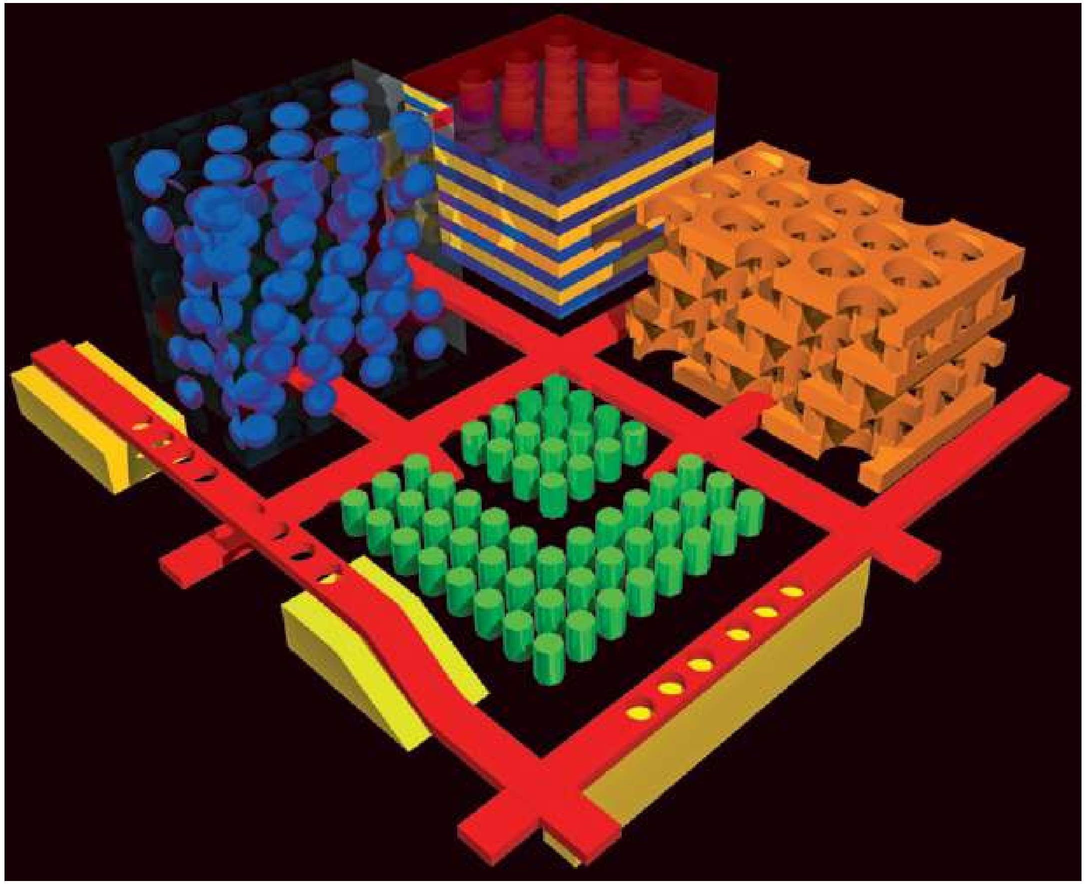


Quantum Optics in Wavelength Scale Structures

SFB Summer School
Blaubeuren
July 2012

J. G. Rarity
University of Bristol
john.rarity@bristol.ac.uk

Confining light: periodic dielectric structures
Photonic crystals



From; Photonic Crystals: Moulding the Flow of Light, Joannopoulos et al, 2008, Princeton University Press

Quantum optics in wavelength scale structures

Motivation

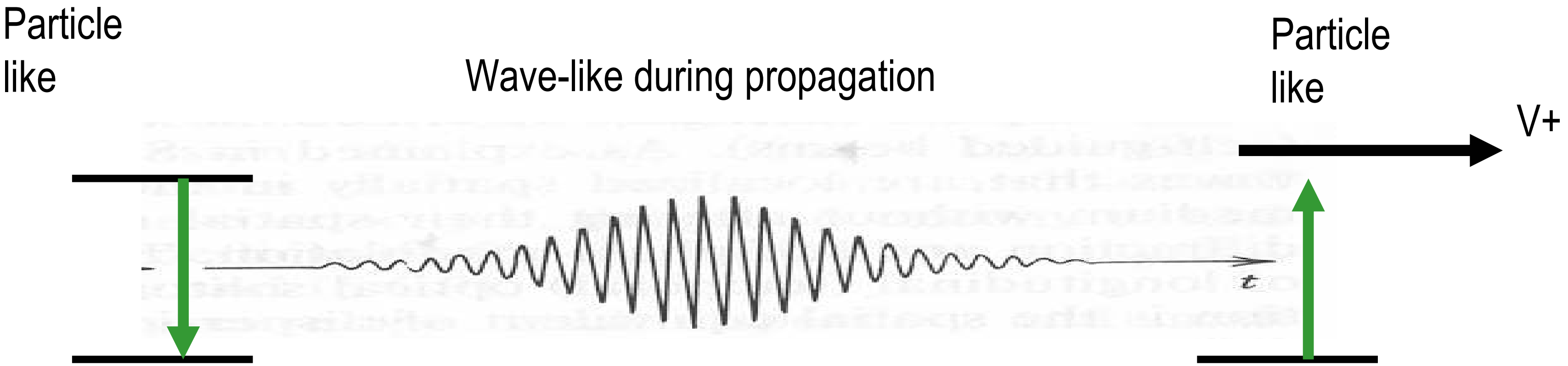
More efficient

- single photon sources
- gates, Hybrid QIP.

Content

- 2-level system in a cavity
- Charged quantum dots in cavity
- Spin-photon interface
- Quantum repeater
- Progress towards experiment

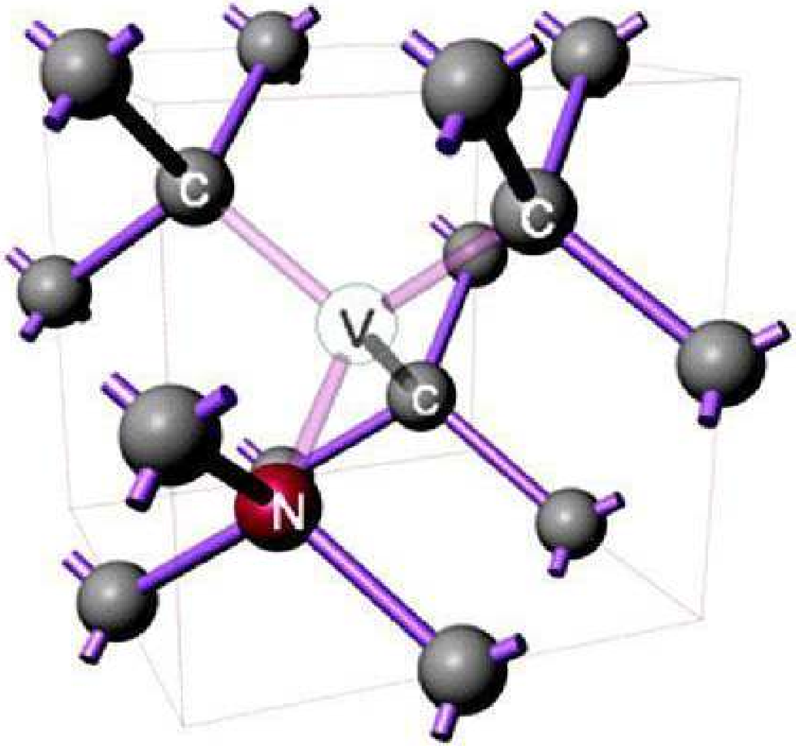
True single photon sources

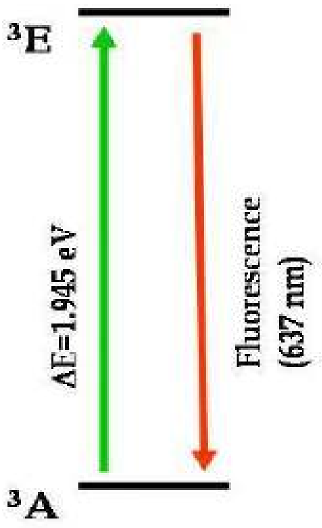


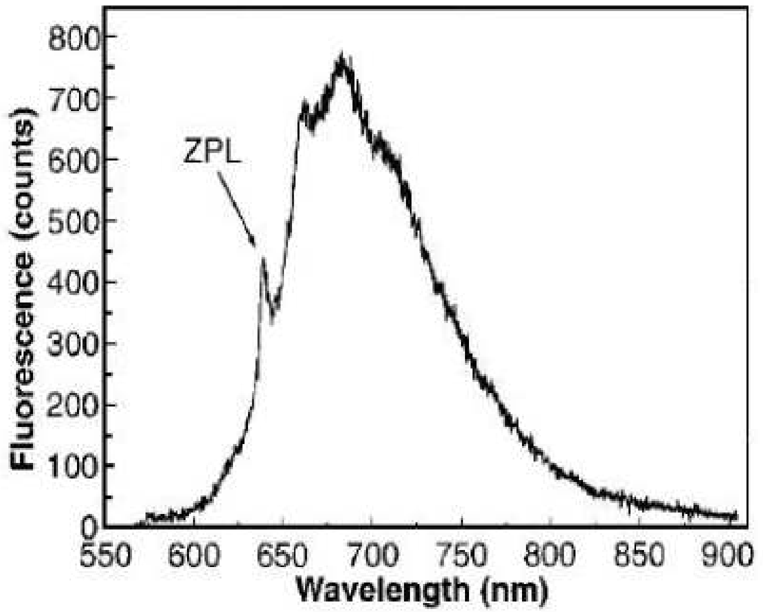
Single atom or ion (in a trap)
Single dye molecule
Single colour centre (diamond NV)
Single quantum dot (eg InAs in GaAs)

Key problem: how to get single photons from source efficiently coupled into single spatial mode

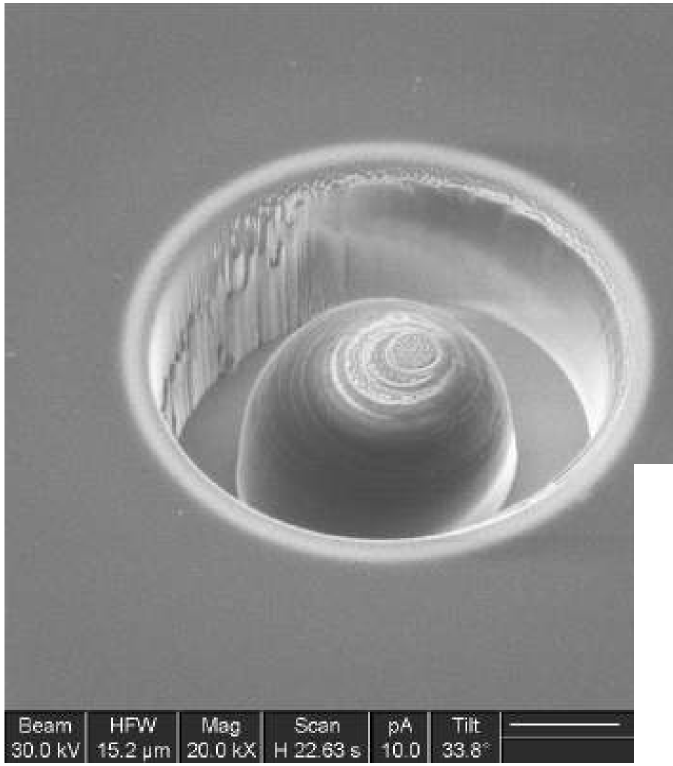
Single photons from NV$^-$ centres in diamond

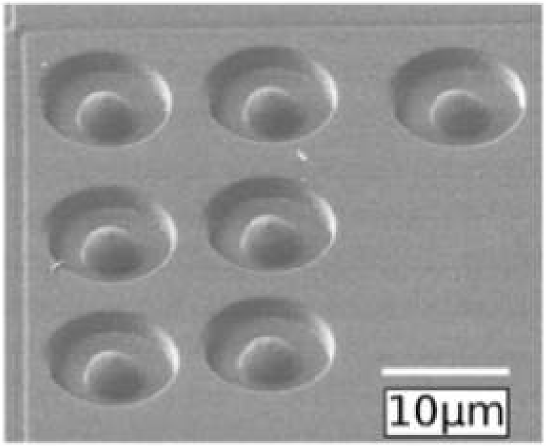


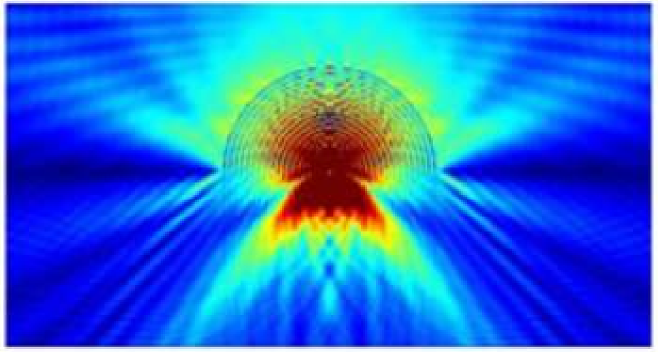




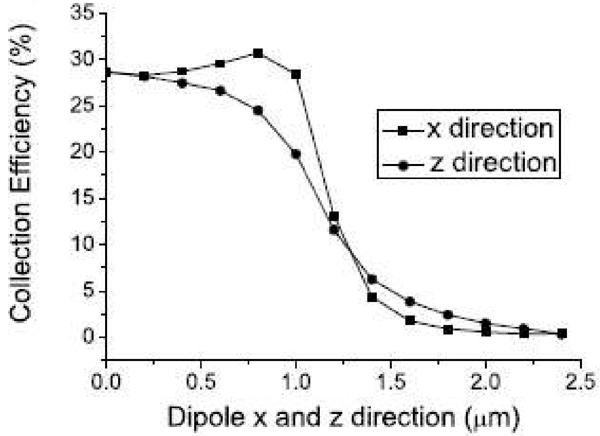
Solid immersion lens fabricated on diamond using focussed ion beam

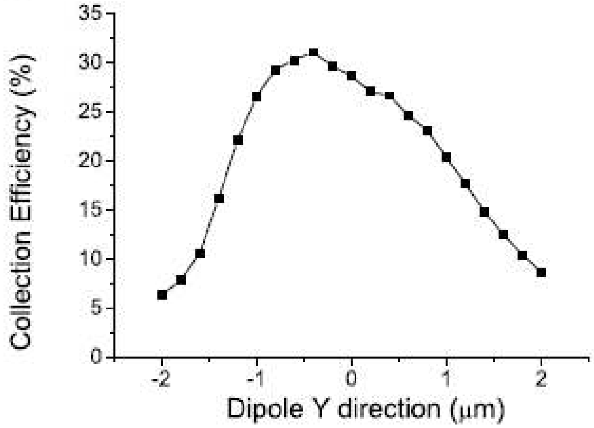






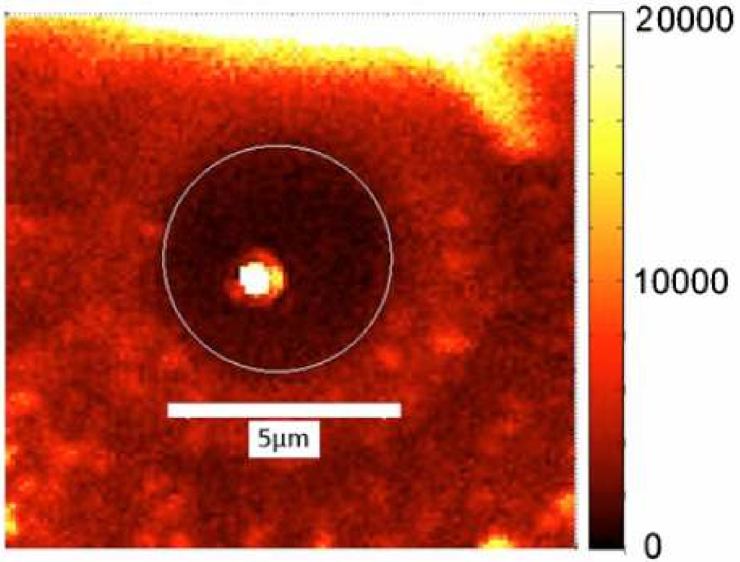
FDTD simulation

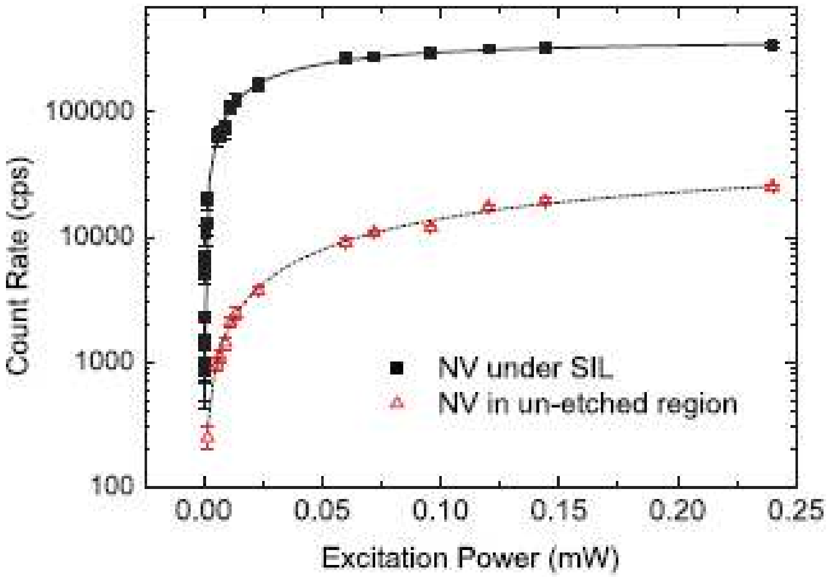




~5% collection into 0.9NA lens from flat surface

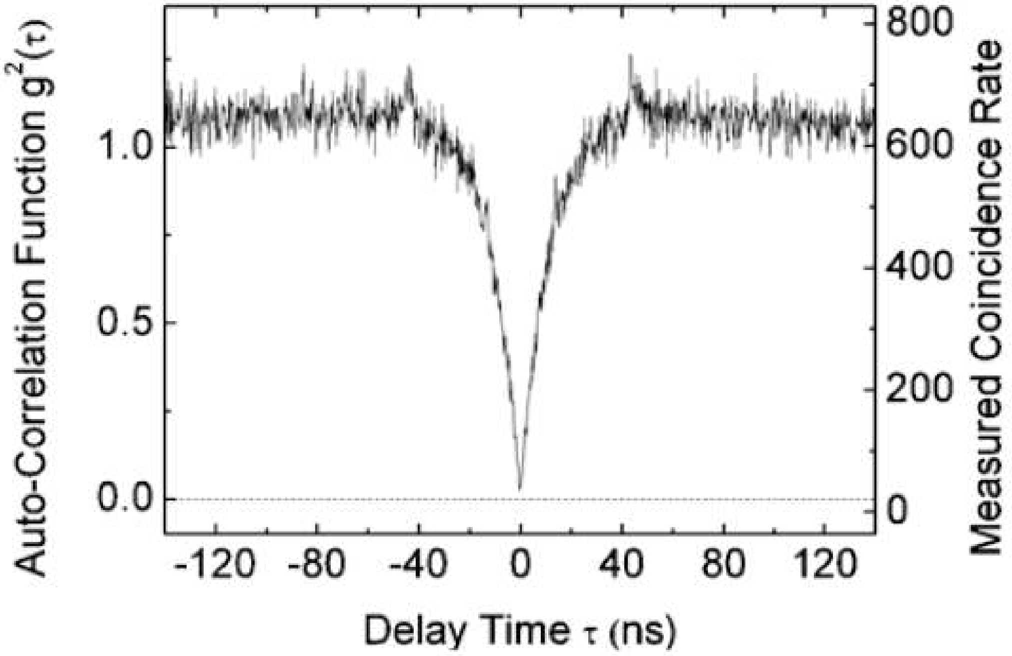
~30% collection into SIL + 0.9NA lens





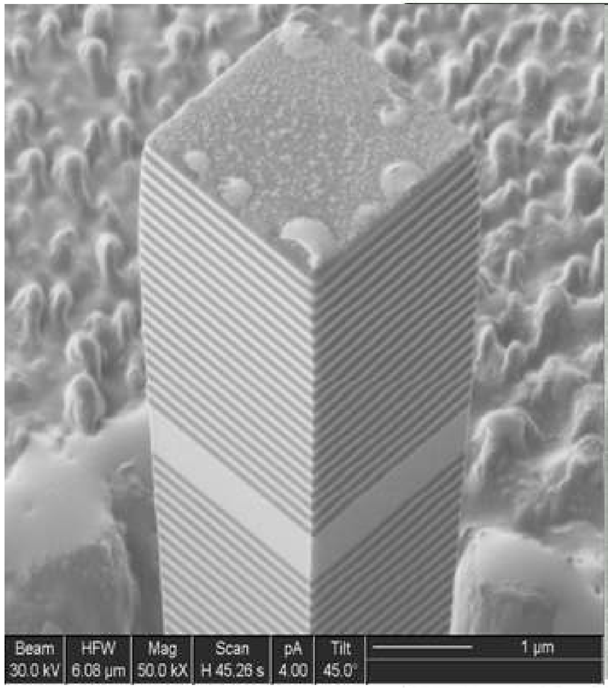
- Serendipitous discovery of single NV centres under SILs on Polycrystalline diamond (E6)

J.P. Haddon et al
APL **97**, 241901 2010

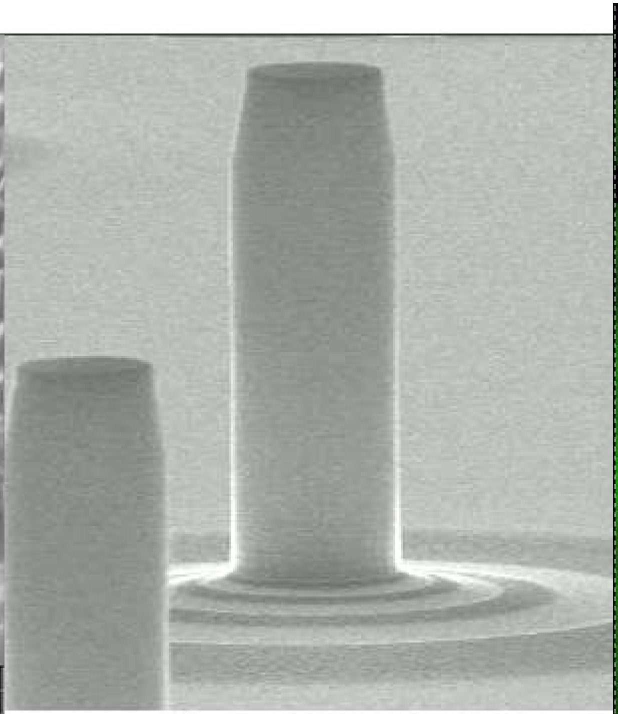


QUANTUM DOTS IN MICRO CAVITIES: SINGLE PHOTON SOURCES

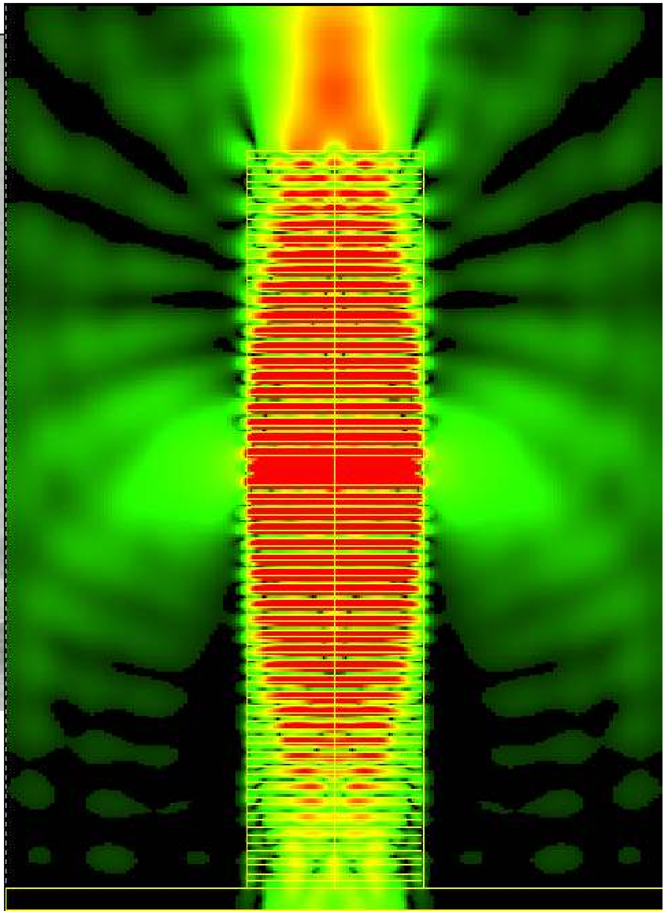
Pillar microcavities for enhanced out-coupling of photons from single quantum dots



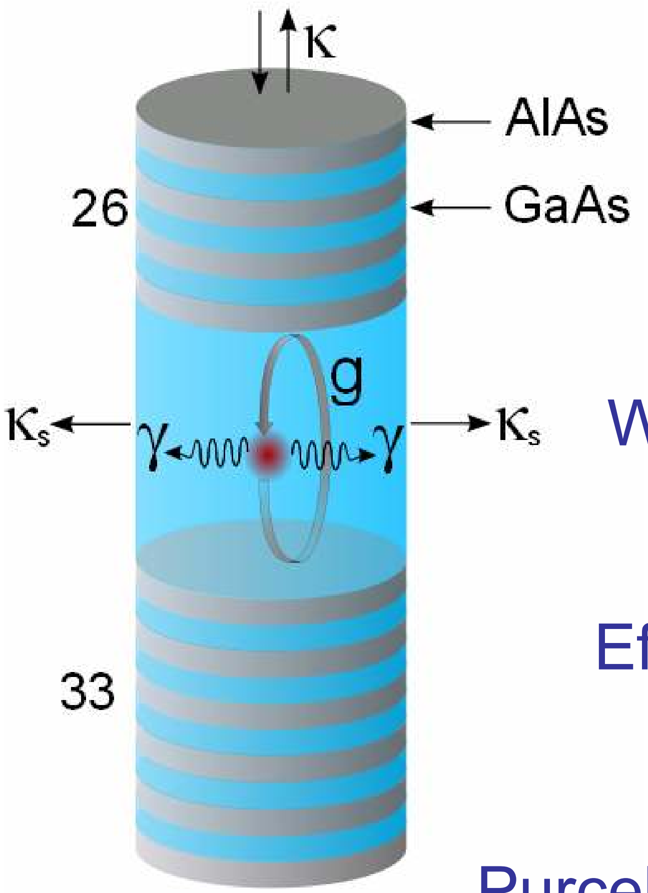
FIB etching



ICP/RIE etching



Cavity Quantum Electrodynamics (CQED)
Weak coupling



QD dipole decay rate γ

Cavity decay rate $$\kappa + \kappa_s = \frac{\omega}{Q} = {}^{1}\!/_{\tau}$$

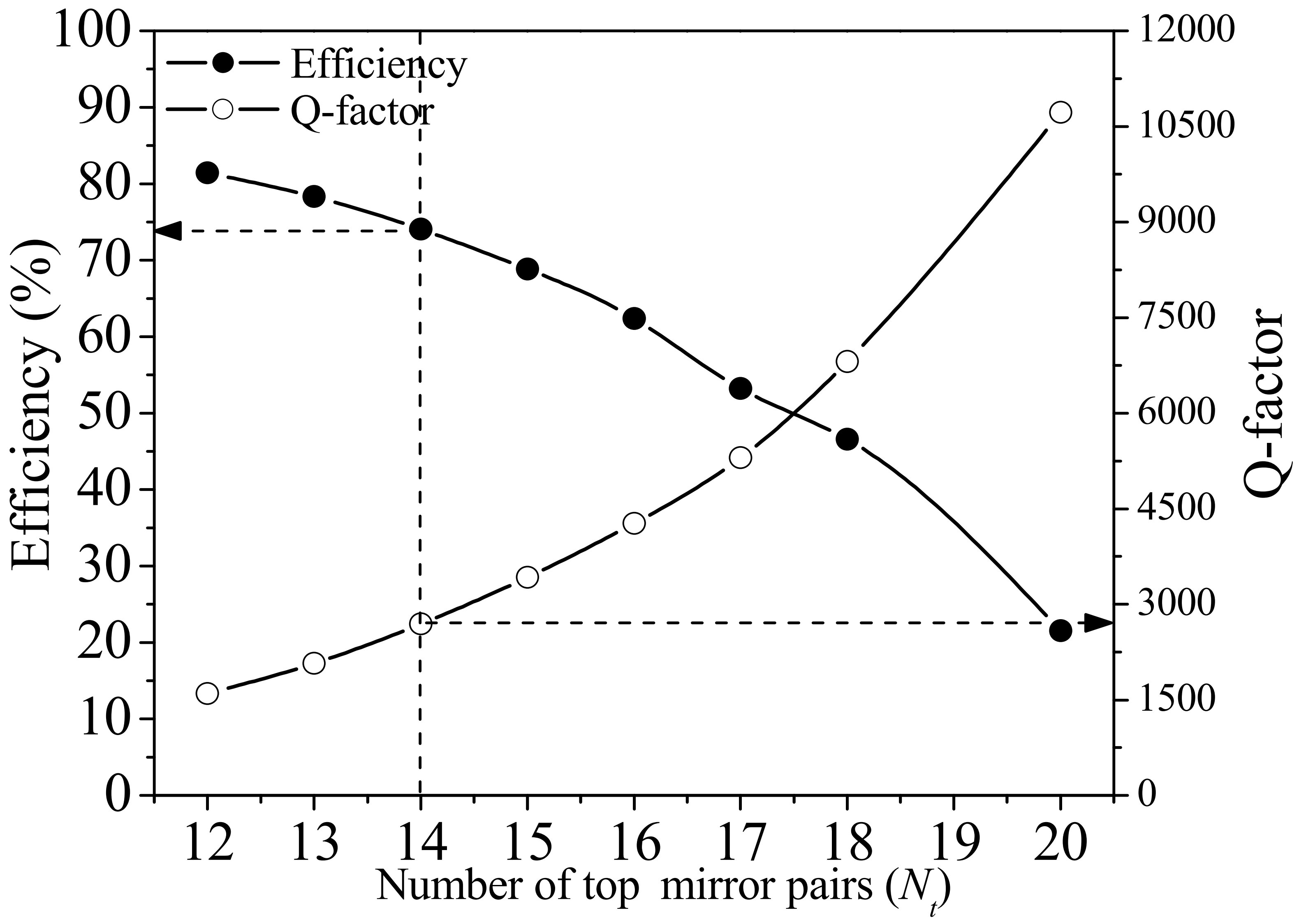
Weak cavity coupling $$g << \kappa + \kappa_s, \gamma$$

Efficiency $$\eta \sim \frac{\kappa}{\kappa + \kappa_s}$$

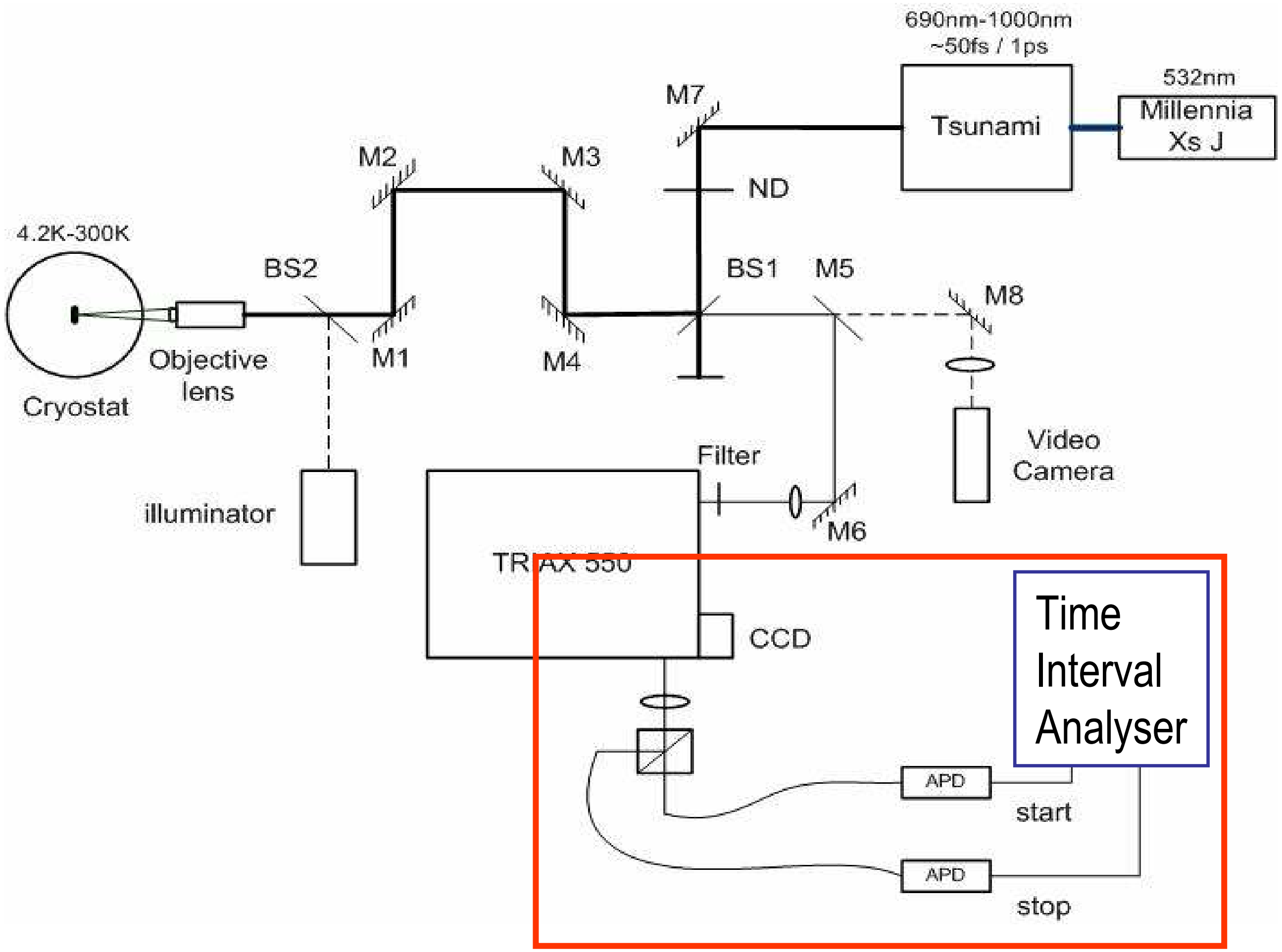
Purcell Factor $$P \sim 1 + \frac{3Q\left({}^{\lambda}\!/_{n}\right)^3}{4\pi^2 V_{eff}}$$

University of BRISTOL

FDTD simulations: 0.50 μm



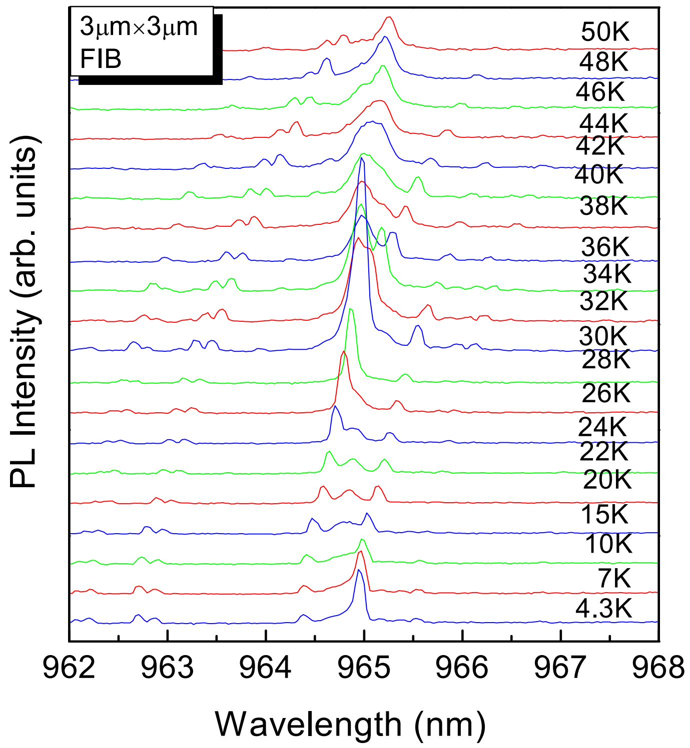
Experimental Setup

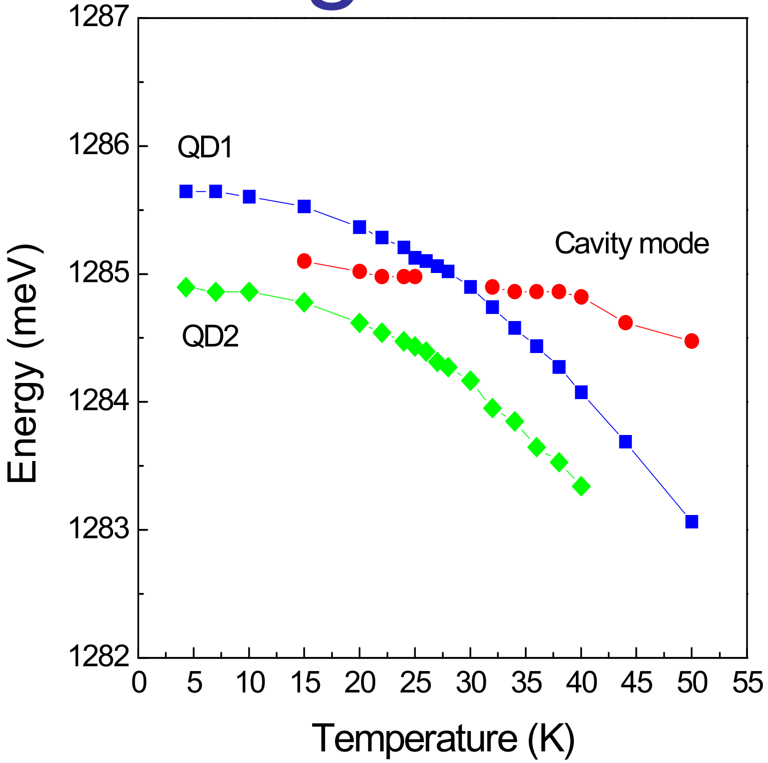


Hanbury-Brown Twiss measurement

$$g^{(2)}(\tau) = \frac{< n(t)n(t+\tau) >}{< n >^2} \sim \frac{p(t:t+\tau)}{p(t)}$$

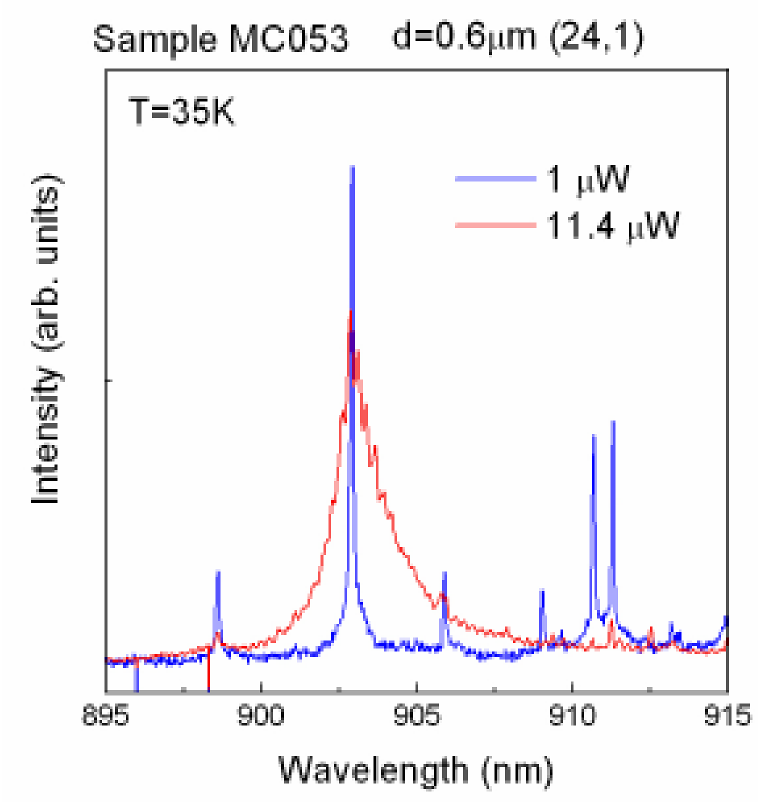
Single QD emission and temperature tuning

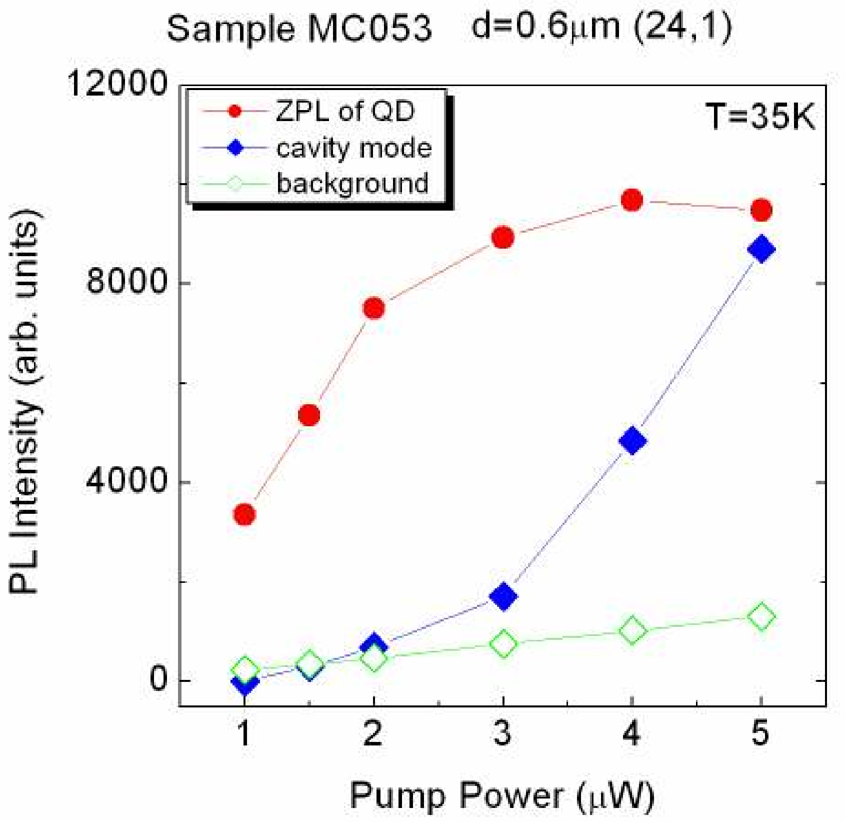




- Single QD emission can be observed in smaller pillar at low excitation power
- QD emission line shifts faster than cavity mode

Single photon generation in circular pillars

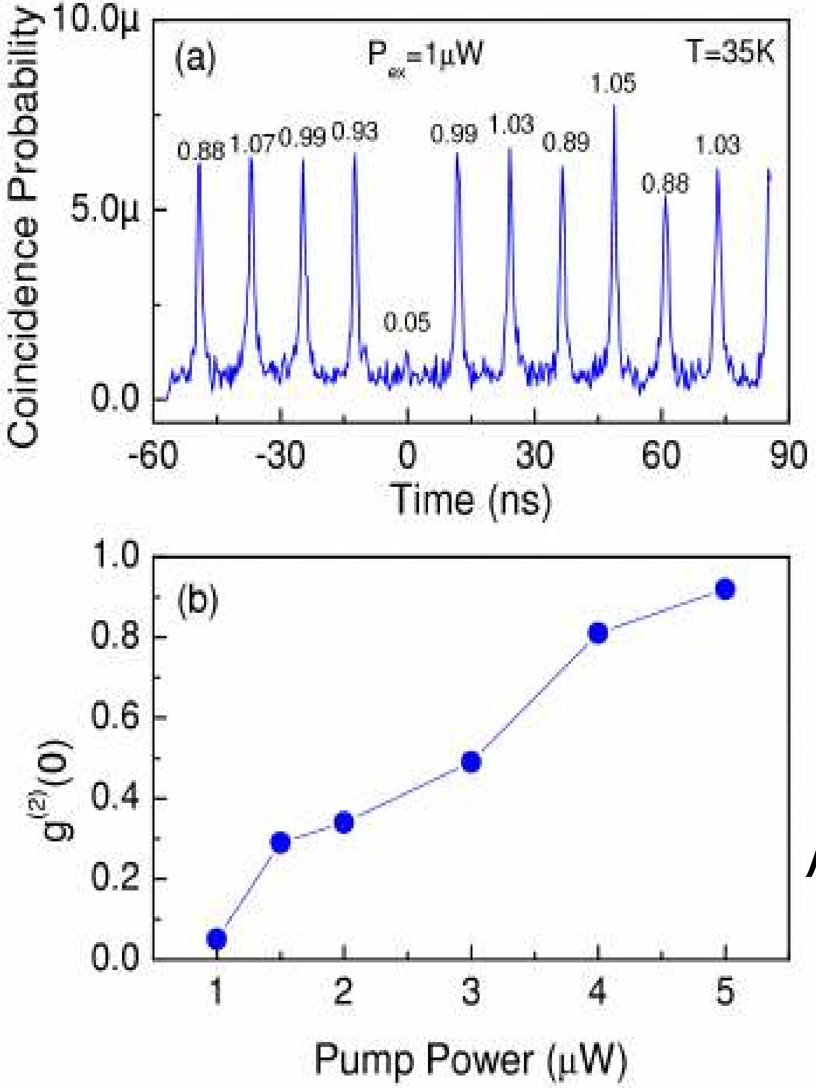




With increasing excitation power

- QD emission saturates
- Cavity mode intensity develops

Single photon generation in circular pillars



- $g^{(2)}(0)=0.05$ indicates multi-photon emission is 20 times suppressed.
- $g^{(2)}(0)$ increases with pump power due to the cavity mode

$$g_b^{(2)}(\tau)=\rho^2\left(g^{(2)}(\tau)-1\right)+1$$

$$\rho=\frac{I_{signal}}{I_{signal}+I_{cavity}+I_{background}}$$

$$g_b^{(2)}(0)=1-\rho^2$$

Progress outside Bristol

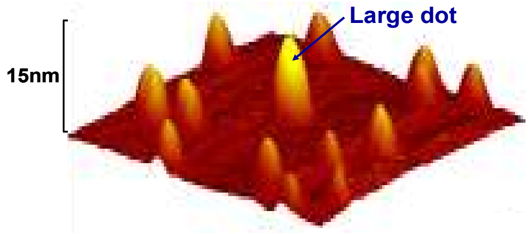
UNIVERSITY OF CAMBRIDGE
TOSHIBA

Single-photon sources

- Optically driven with multiphoton emission <2%
- 1.3μm single photons: Quantum Key Distribution demonstrated over 35km
- Electrically driven single-photon sources Single photon LED
- HoM Interference demonstrated between separate photons from the same QD (75% visibility)

Bennett et al, Optics Exp 13, 7778 (2005)

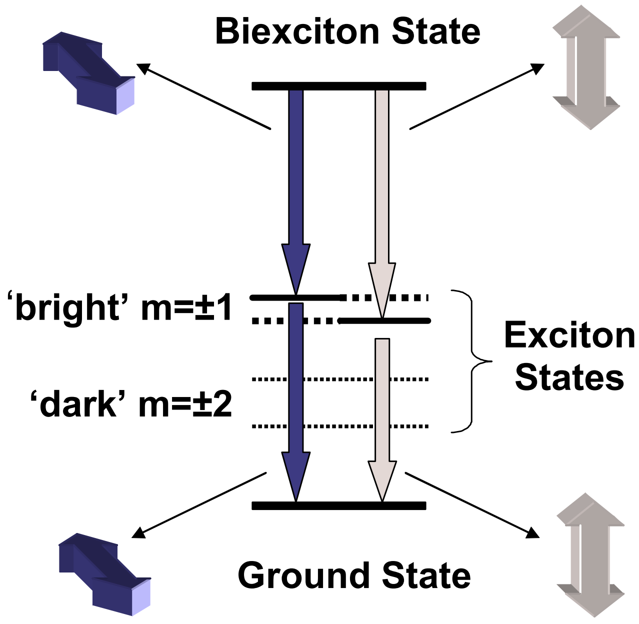
Journal of Optics B **7,** 129-136 (2005).



Entangled photon pairs from Biexciton Exciton cascaded emission

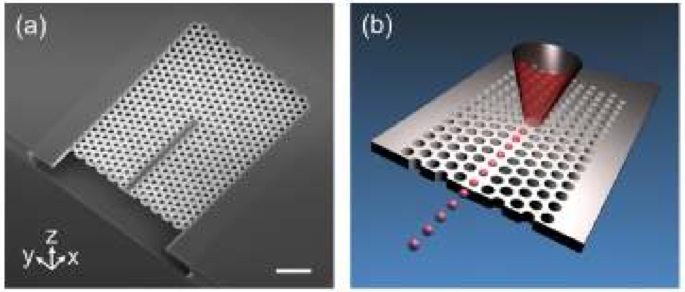
Nature **439**, 179-182, PRL 102, 030406 (2009),

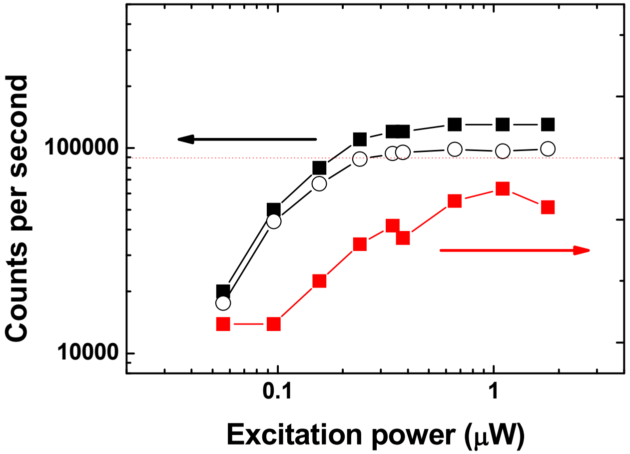
Douce et al., Nature 466, 217 (2010)

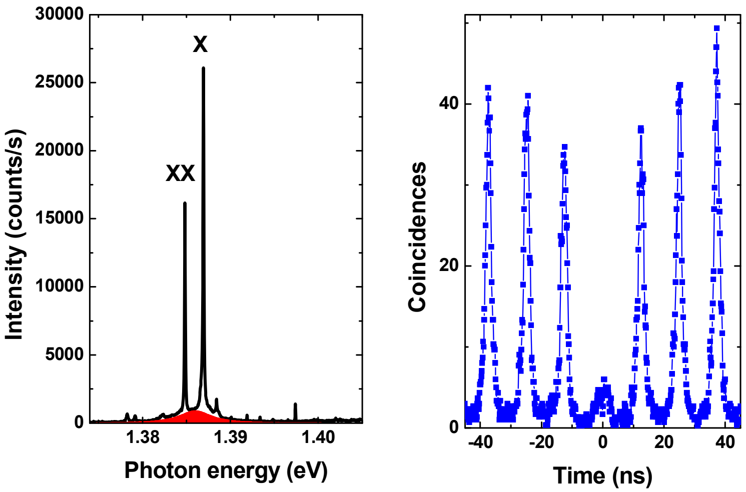


On-chip generation and transmission of single-photon

- In-plane emission of single photons from a semiconductor QD.



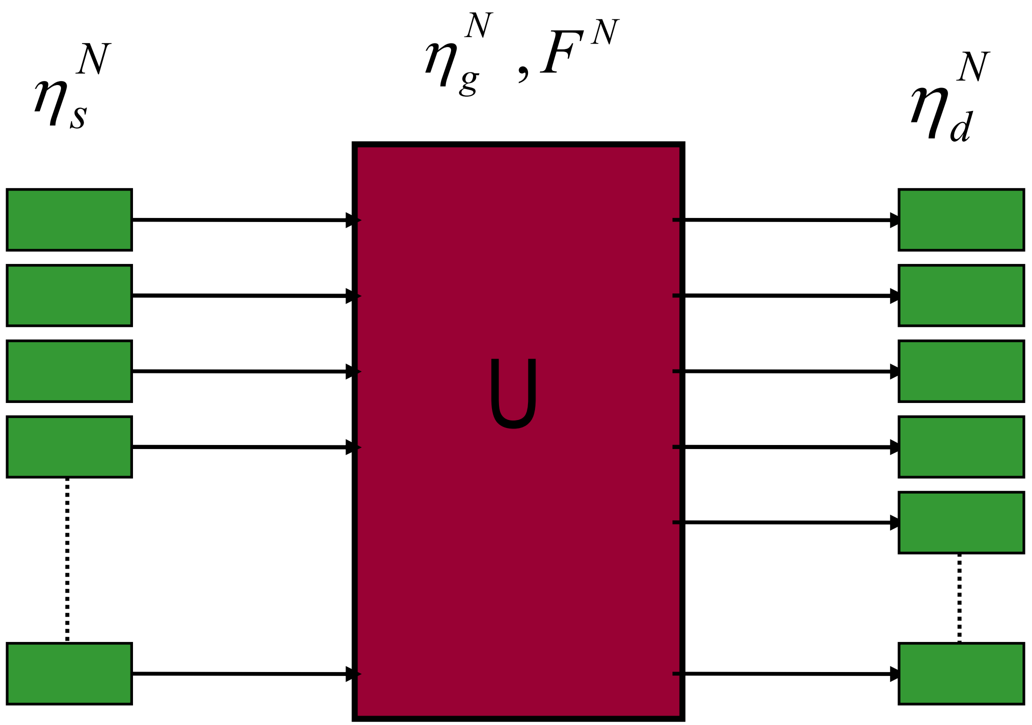




More details: *Appl. Phys. Lett.* 99, 261108 (2011)

Hybrid QIP

The PROBLEM: many qubits quantum processor


η_s^N

η_g^N, F^N

η_d^N

Single Qubit source

Single 2-level ~ 2-10%
Heralded from pair ~ 80%

Unitary transform

Linear gates η<0.5 F>0.99
Non-linear optics η~1 F>0.9?

Detectors

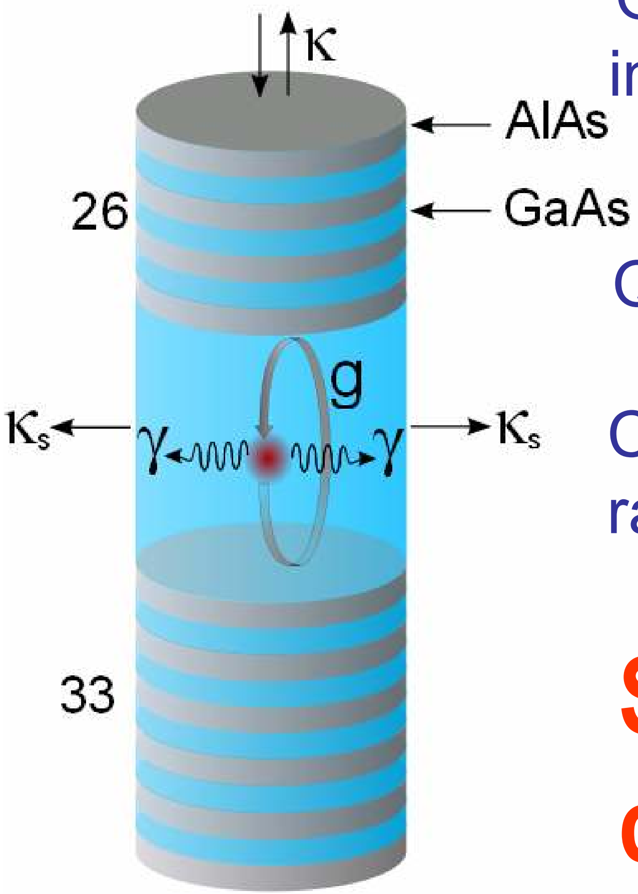
Si 600-800nm ~70% (100%?)
InGaAs 1.3-1.6um ~30%
Superconducting~10-88%

Throughput~ $\eta_s^N \eta_d^N \eta_g^N .f(F).R$

Spin photon interface using charged quantum dots in microcavities

C.Y. Hu, A. Young, J. L. O’Brien, W.J. Munro, J. G. Rarity, Phys. Rev. B 78, 085307 (08)
C.Y. Hu, W.J. Munro, J. G. Rarity, Phys. Rev. B 78, 125318 (08)
C.Y. Hu, W.J. Munro, J. L. O’Brien , J. G. Rarity, Arxiv: 0901.3964(09)
C.Y. Hu, J. G. Rarity, Arxiv: 1005.5545, PRB XX, XXX (2011)

Cavity Quantum Electrodynamics (CQED)



QD-cavity interaction $$g=\sqrt{\frac{\hbar^2}{4\pi\varepsilon_r\varepsilon_0}\frac{\pi e^2 f}{mV_{\text{eff}}}}$$

f=oscillator strength
m= electron effective mass
V= cavity volume

QD dipole decay rate γ

Cavity decay rate $$\kappa+\kappa_s=\frac{\hbar\omega}{Q}$$

Strong coupling $$g>\frac{\kappa+\kappa_s}{4}$$

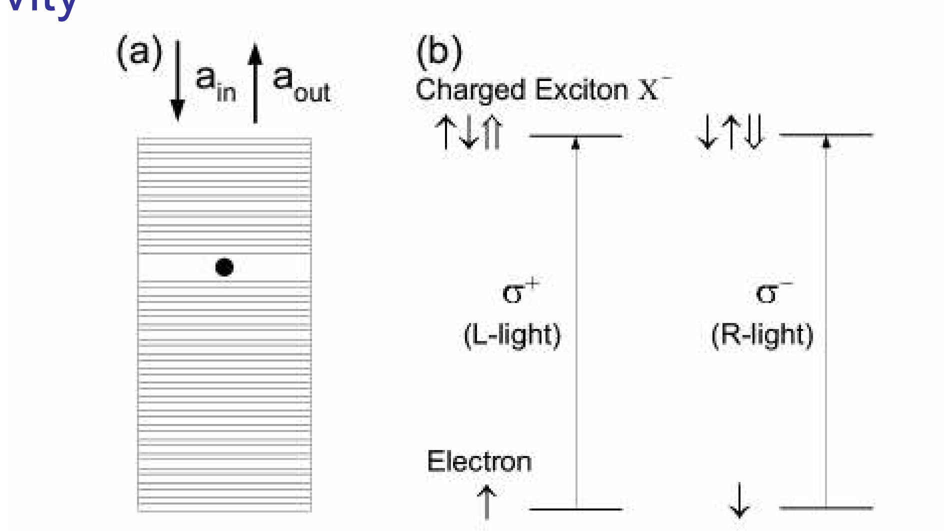
To optimise g/κ

Maximise $\boldsymbol{Q/V^{1/2}}$

Giant optical Faraday rotation

C.Y. Hu, Rarity et al, Phys. Rev. B 78, 085307 (08)
C.Y. Hu, Rarity et al, Phys. Rev. B 78, 125318 (08)

Single-sided cavity



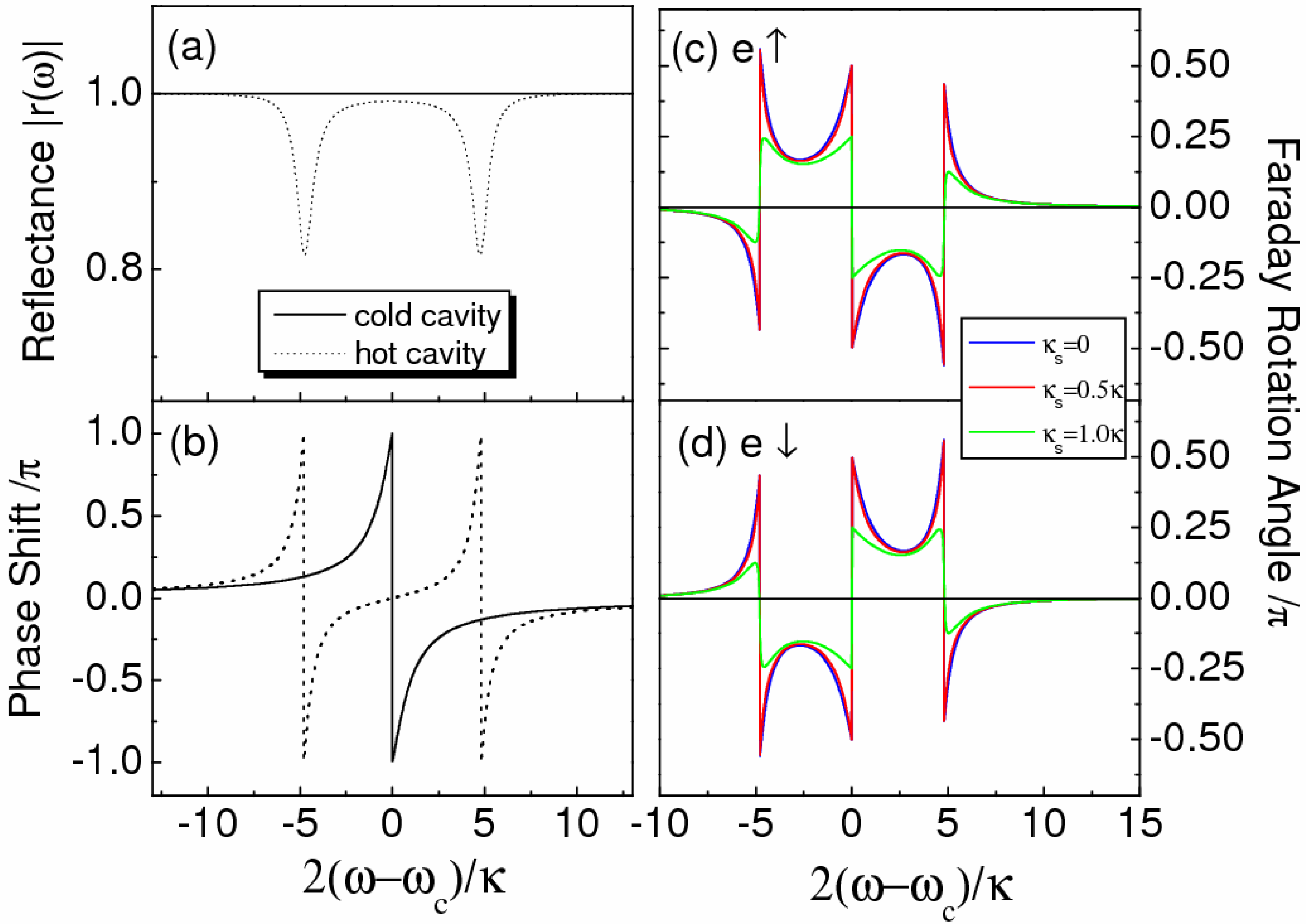
Reflection coefficient

Cold Cavity $g = 0 \quad |r(\omega)| = 1 \quad \varphi_0(\omega) = \pm\pi + 2\tan^{-1}\frac{2(\omega - \omega_c)}{\kappa}$

Hot cavity $g >> \kappa, \gamma \quad r(\omega \sim \omega_c) = 1$

Phase shift gate

$$\hat{U}(\Delta\varphi) = e^{i\Delta\varphi\left(|L\rangle\langle L|\otimes|\uparrow\rangle\langle\uparrow| + |R\rangle\langle R|\otimes|\downarrow\rangle\langle\downarrow|\right)}$$


(a)
Reflectance $|r(\omega)|$
1.0
0.8
cold cavity
hot cavity
(b)
Phase Shift $/\pi$
1.0
0.5
0.0
-0.5
-1.0
-10
-5
0
5
10
$2(\omega-\omega_c)/\kappa$
(c) e↑
(d) e↓
$\kappa_s=0$
$\kappa_s=0.5\kappa$
$\kappa_s=1.0\kappa$
0.50
0.25
0.00
-0.25
-0.50
Faraday Rotation Angle $/\pi$
-10
-5
0
5
10
15
$2(\omega-\omega_c)/\kappa$

Giant optical Faraday rotation

- Electron spin ↑, L-light feels a hot cavity and R-light feels a cold cavity
- Electron spin ↓, R-light feels a hot cavity and L-light feels a cold cavity
- By suitable detuning can arrange orthogonal, Giant Faraday rotation angle

$$\theta_F^{\uparrow} = \frac{\varphi_0 - \varphi}{2} = -\theta_F^{\downarrow} = 45^0 \qquad \Delta\varphi > \frac{\pi}{2}$$

Achievable with

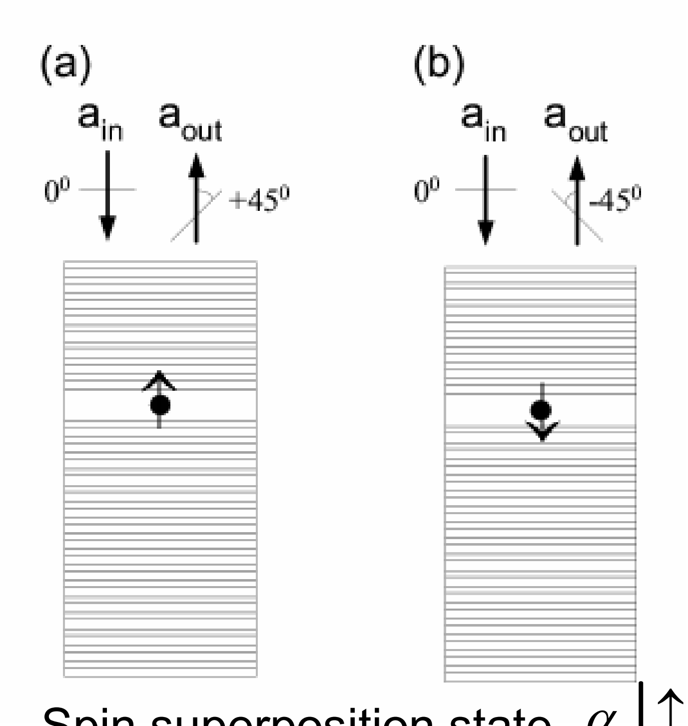
$$\frac{g}{(\kappa + \kappa_s)} > 0.1 \qquad \kappa/\kappa_s \sim 1$$

Low efficiency

$$\frac{g}{(\kappa + \kappa_s)} > 1.5 \qquad \kappa/\kappa_s >> 1$$

High efficiency

Quantum non-demolition detection of a single electron spin



Input light $|H\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$

Spin up

$$|H\rangle\otimes|\uparrow\rangle \xrightarrow{\dot{U}(\pi/2)} \frac{1}{\sqrt{2}}|+45^0\rangle|\uparrow\rangle$$

Spin down

$$|H\rangle\otimes|\downarrow\rangle \xrightarrow{\dot{U}(\pi/2)} \frac{1}{\sqrt{2}}|-45^0\rangle|\downarrow\rangle$$

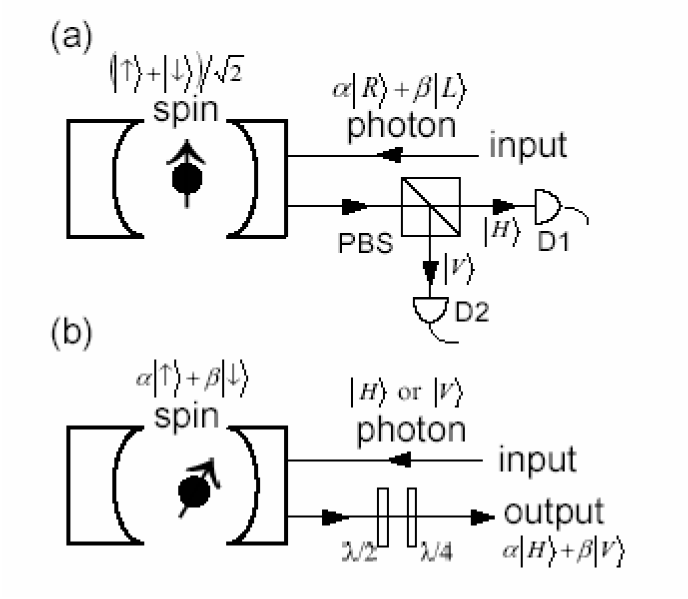
Spin superposition state $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$

$$\boxed{|H\rangle\otimes(\alpha|\uparrow\rangle+\beta|\downarrow\rangle) \rightarrow \frac{1}{\sqrt{2}}\left\{\alpha|+45^0\rangle|\uparrow\rangle+\beta|-45^0\rangle|\downarrow\rangle\right\}}$$

A photon spin entangler!

C.Y. Hu, et al, Phys. Rev. B 78, 085307 (08)

Photon-spin quantum interface



(a)

State transfer from photon to spin

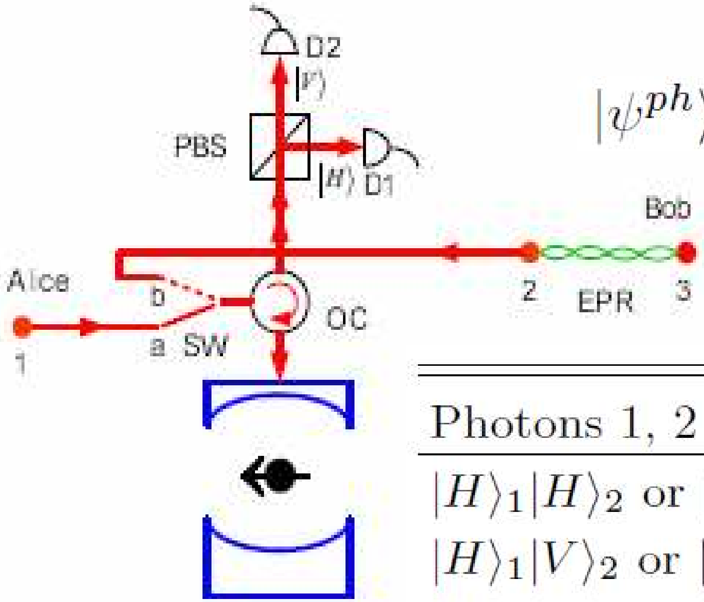
(b)

State transfer from spin to photon

- Deterministic
- High fidelity
- Two sided cavity makes an entangling beamsplitter (Phys Rev B 80, 205326, 2009)

Quantum Repeater: arXiv1005.5545

$$|\psi^{ph}\rangle_1 = \alpha|R\rangle_1 + \beta|L\rangle_1$$

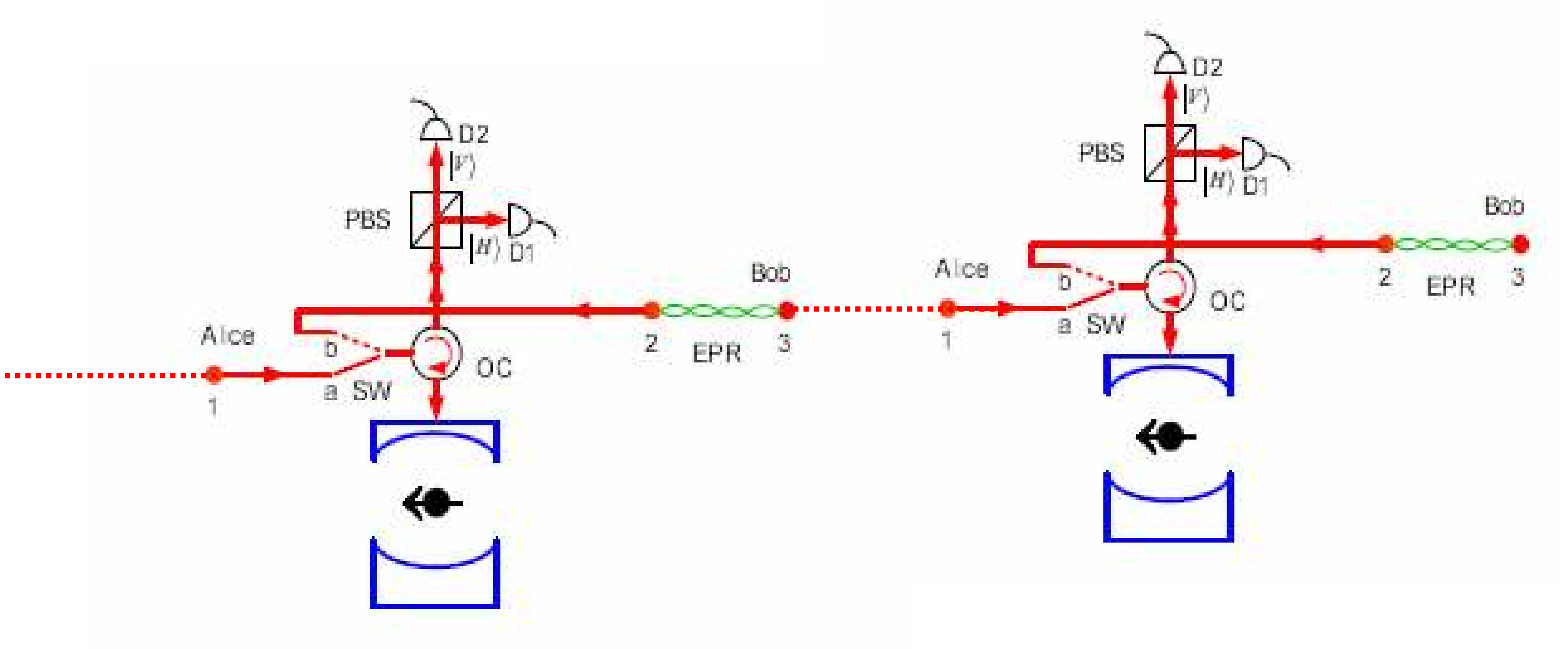


$$|\psi^{ph}\rangle_{23} = (|R\rangle_2|L\rangle_3 + |L\rangle_2|R\rangle_3)/\sqrt{2}$$

$$|\psi^{s}\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$$

Photons 1, 2	Spin	Photon 3
$|H\rangle_1|H\rangle_2$ or $|V\rangle_1|V\rangle_2$	$|-\rangle$	$\alpha|L\rangle_3 - \beta|R\rangle_3$
$|H\rangle_1|V\rangle_2$ or $|V\rangle_1|H\rangle_2$	$|-\rangle$	$\alpha|L\rangle_3 + \beta|R\rangle_3$
$|H\rangle_1|H\rangle_2$ or $|V\rangle_1|V\rangle_2$	$|+\rangle$	$\alpha|R\rangle_3 + \beta|L\rangle_3$
$|H\rangle_1|V\rangle_2$ or $|V\rangle_1|H\rangle_2$	$|+\rangle$	$\alpha|R\rangle_3 - \beta|L\rangle_3$

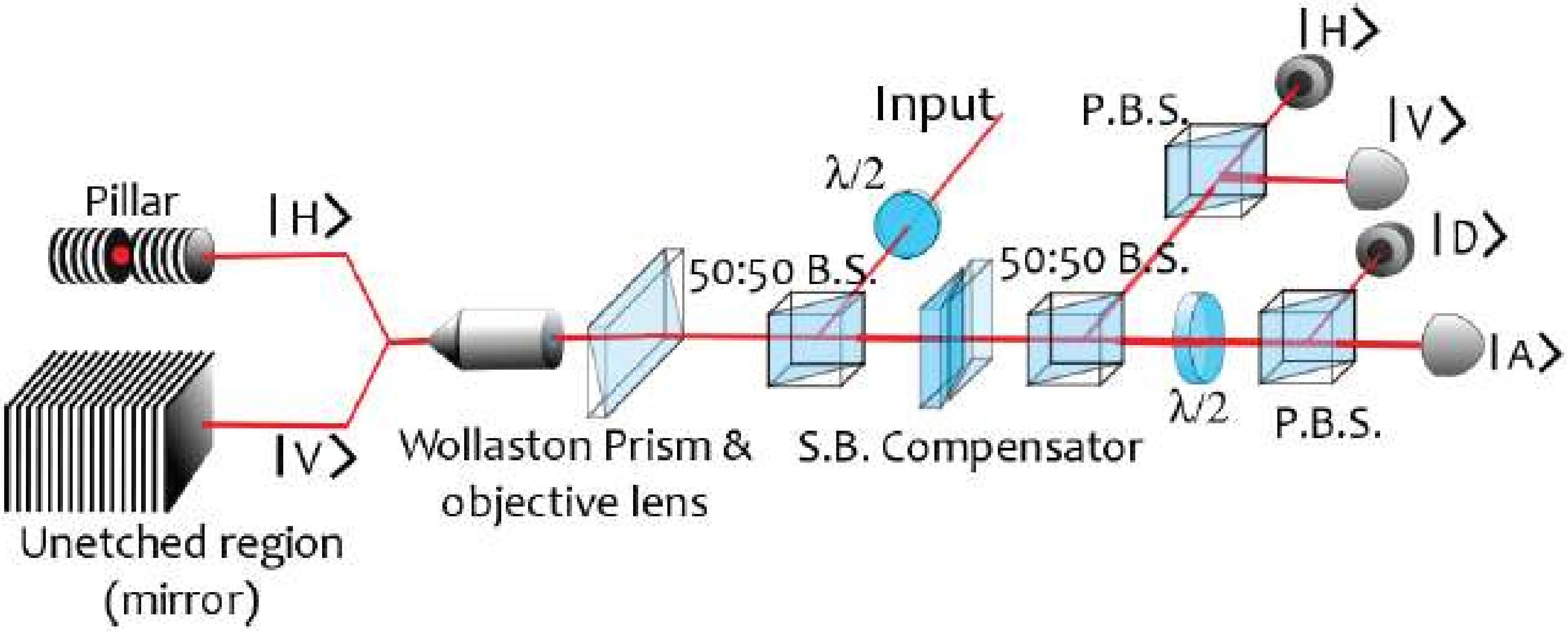
Quantum Repeater: arXiv1005.5545



Experiments

- Strong coupling seen in resonant reflection experiment
- Phase shift between resonant and non-resonant case ~0.2 radians
- Young, Rarity et al arXiv 1011.384, PRB 2011

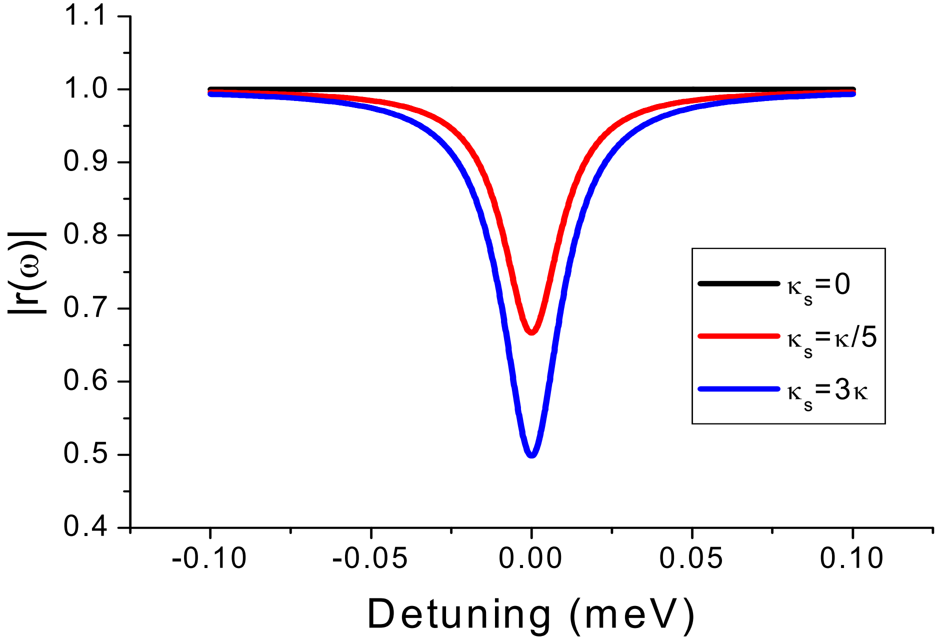
Reflection spectroscopy
Conditional phase shift interferometer

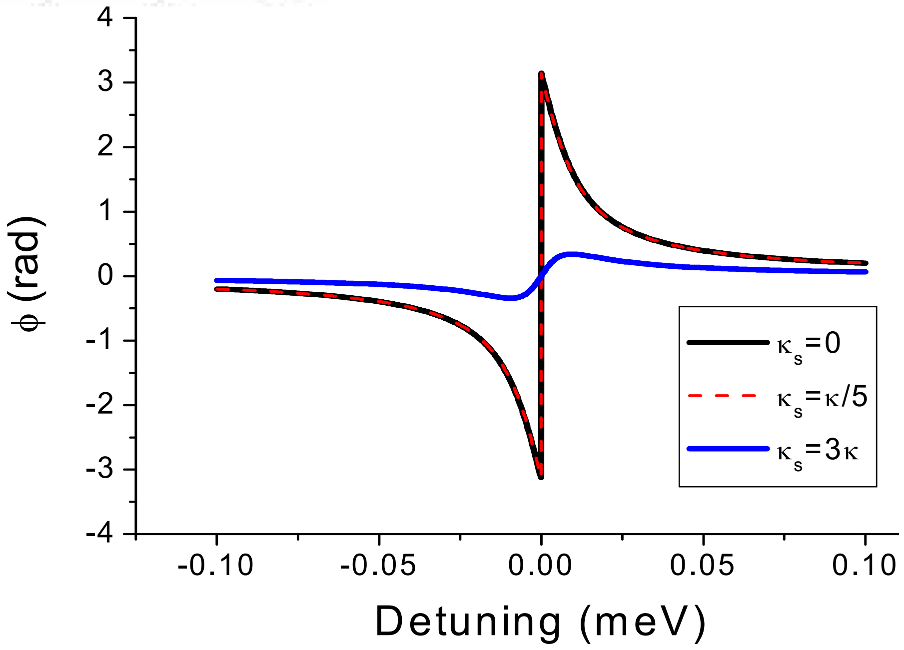


$$\frac{D - A}{\sqrt{V \times H}} = \sin \phi(\omega)$$

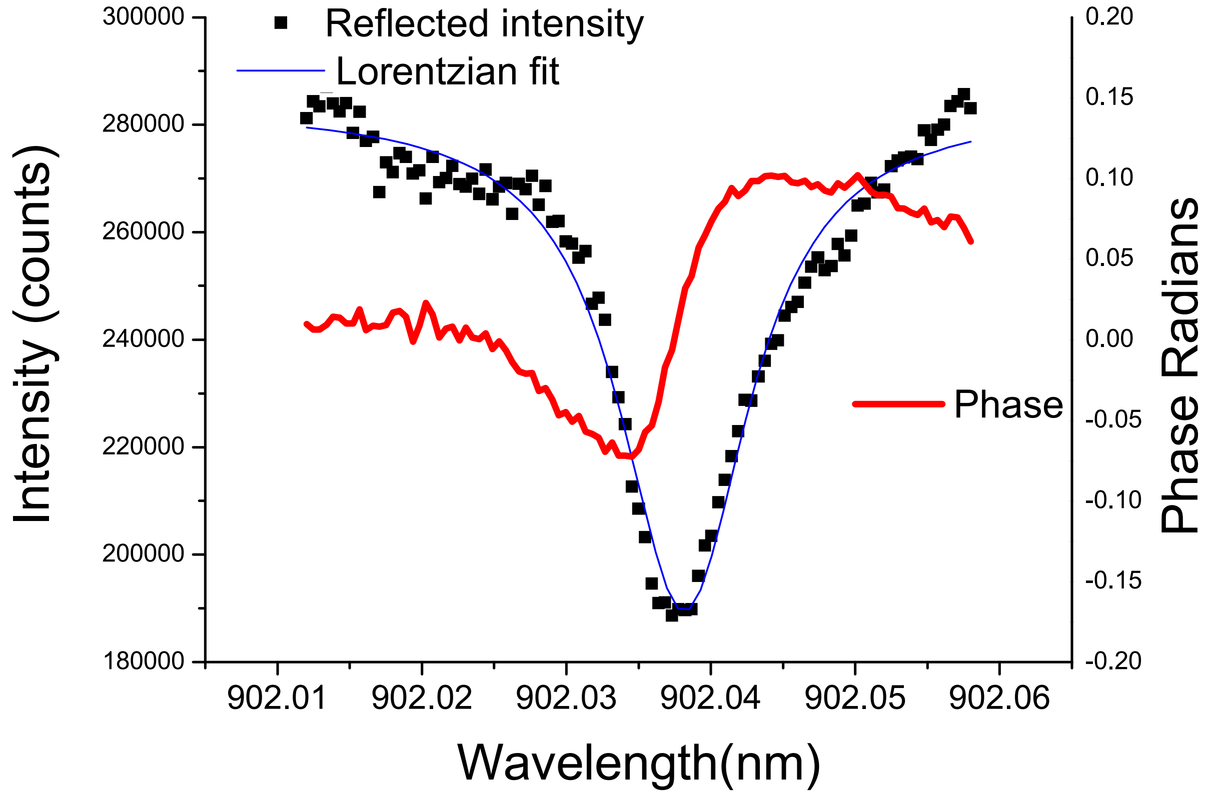
Empty cavity

$$\begin{aligned} r(\omega) &= |r(\omega)|e^{i\phi} \\ &= 1 - \frac{\kappa(i(\omega_{qd}-\omega)+\frac{\gamma}{2})}{(i(\omega_{qd}-\omega)+\frac{\gamma}{2})(i(\omega_c-\omega)+\frac{\kappa}{2}+\frac{\kappa_s}{2})+g^2} \end{aligned}$$

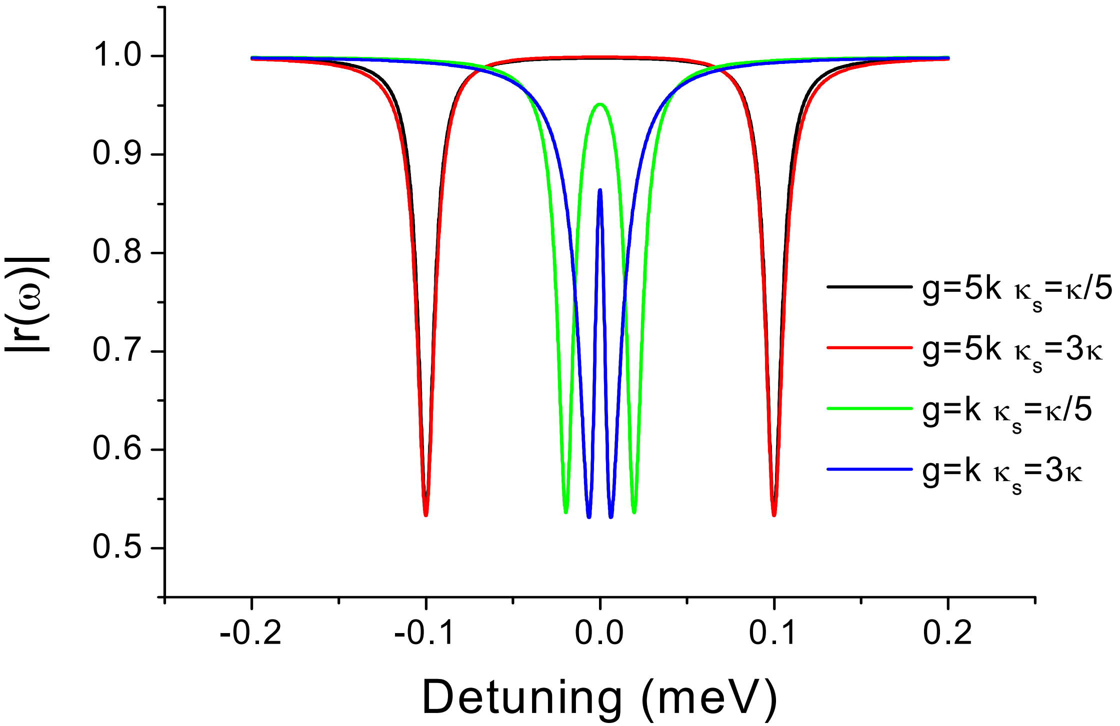




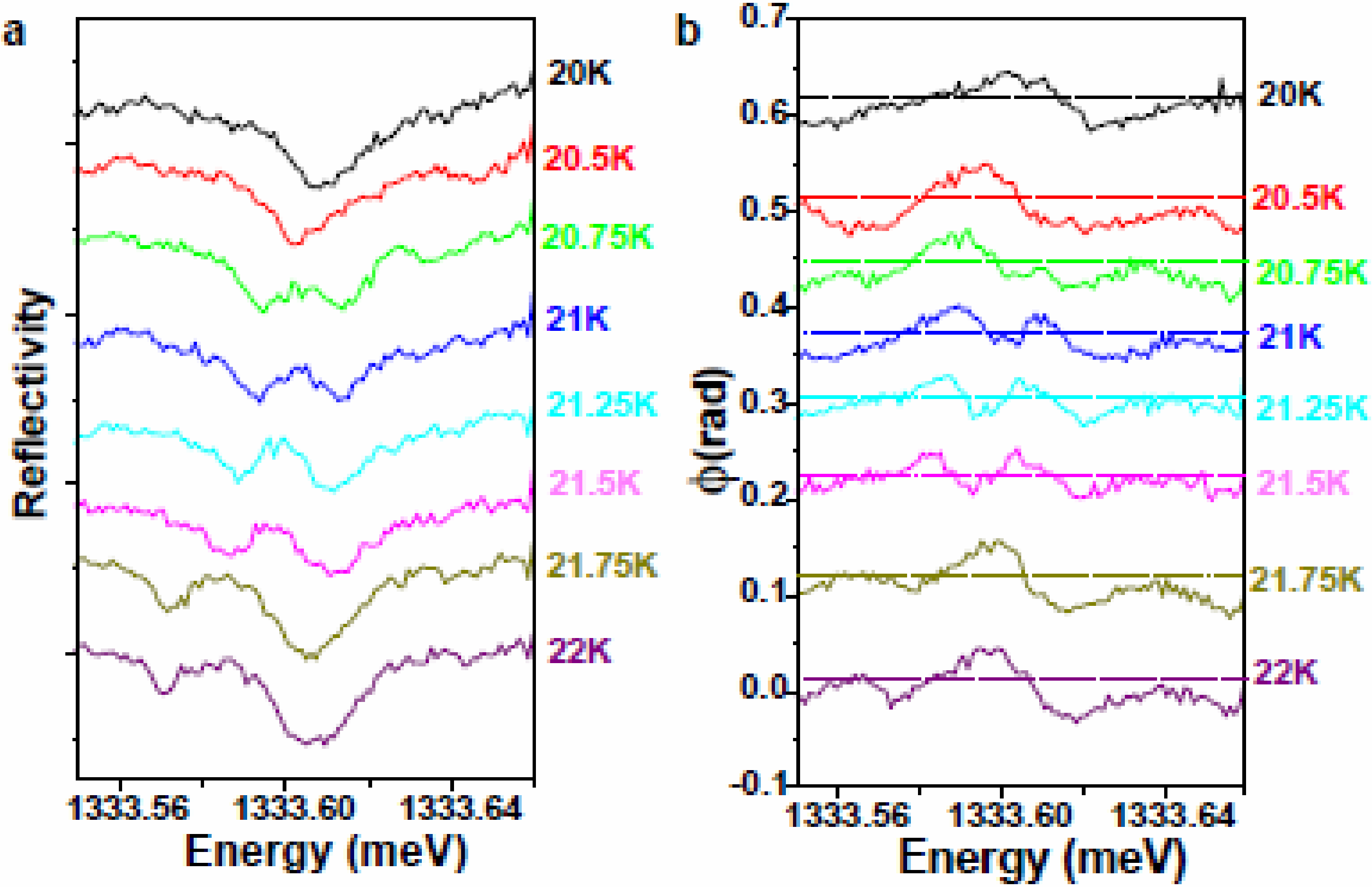
Resonant reflection spectra of an empty 4μ pillar (Q~84000)



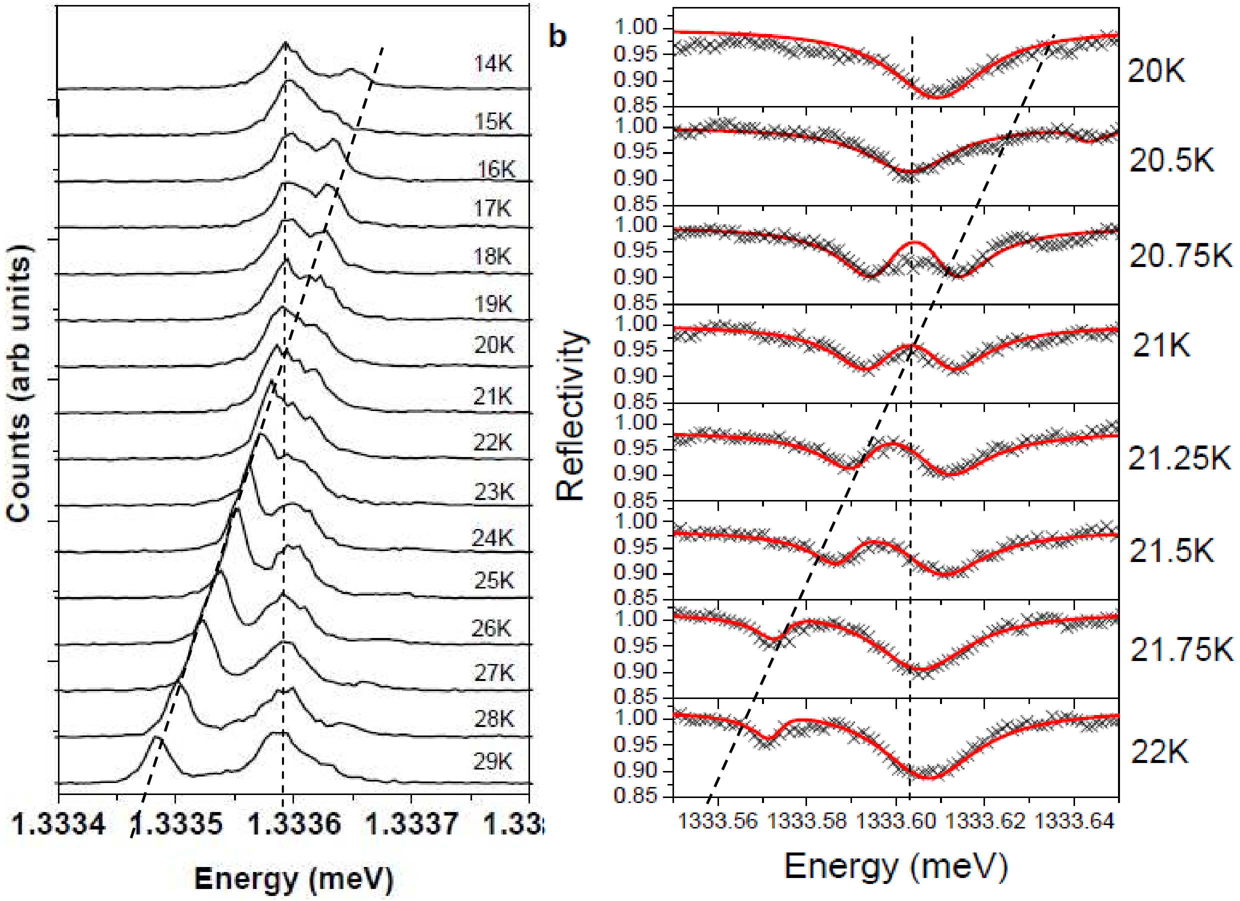
Strongly coupled cavity on resonance



- Resonant reflection spectra of a 2.5μ pillar containing a single dot: temperature tuning to resonance (Q~54000)



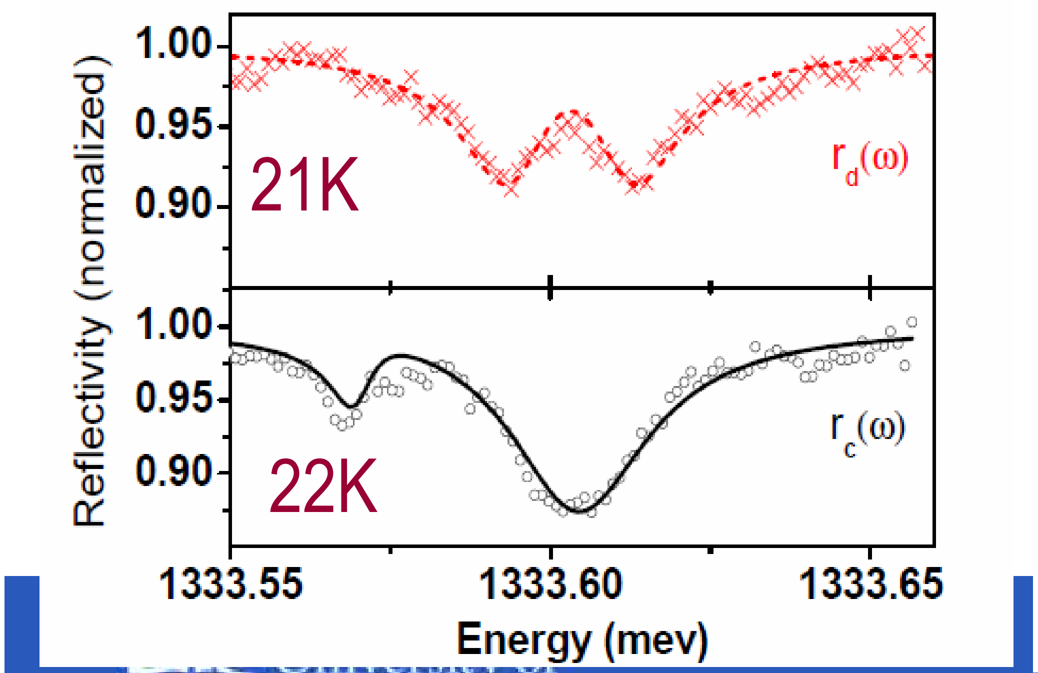
Comparing PL and resonant spectroscopy

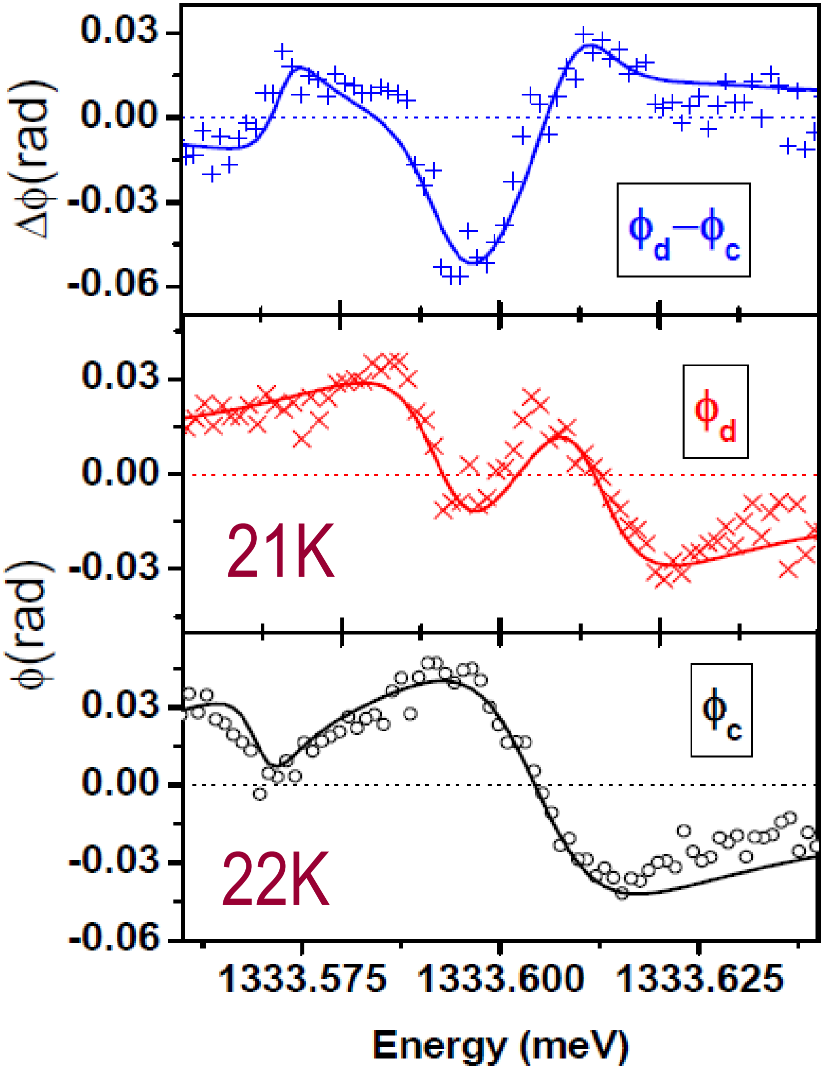


- Conditional phase seen between a dot on and off-resonance with cavity

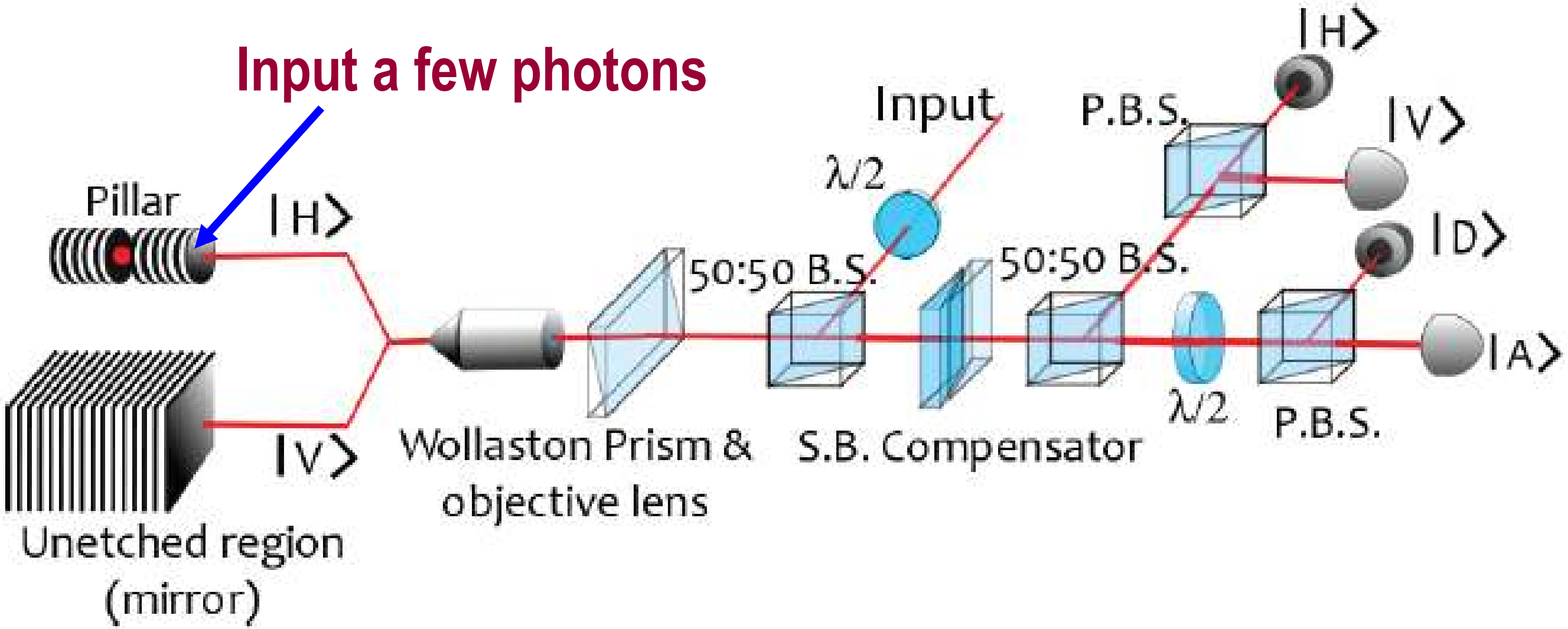
g~9.4ueV $\kappa + \kappa s$ ~ 26ueV γ~5ueV

$g > (\kappa + \kappa s + \gamma)/4$ $\Delta\varphi$~0.05 rad (0.12rad)





Attojoule switch



Input enough photons (1 in principle) to saturate the dot and return to weak coupling.

Change phase of reflection, modulate D and A

All optical switch (1 photon ~0.1 attojoule)

Future:

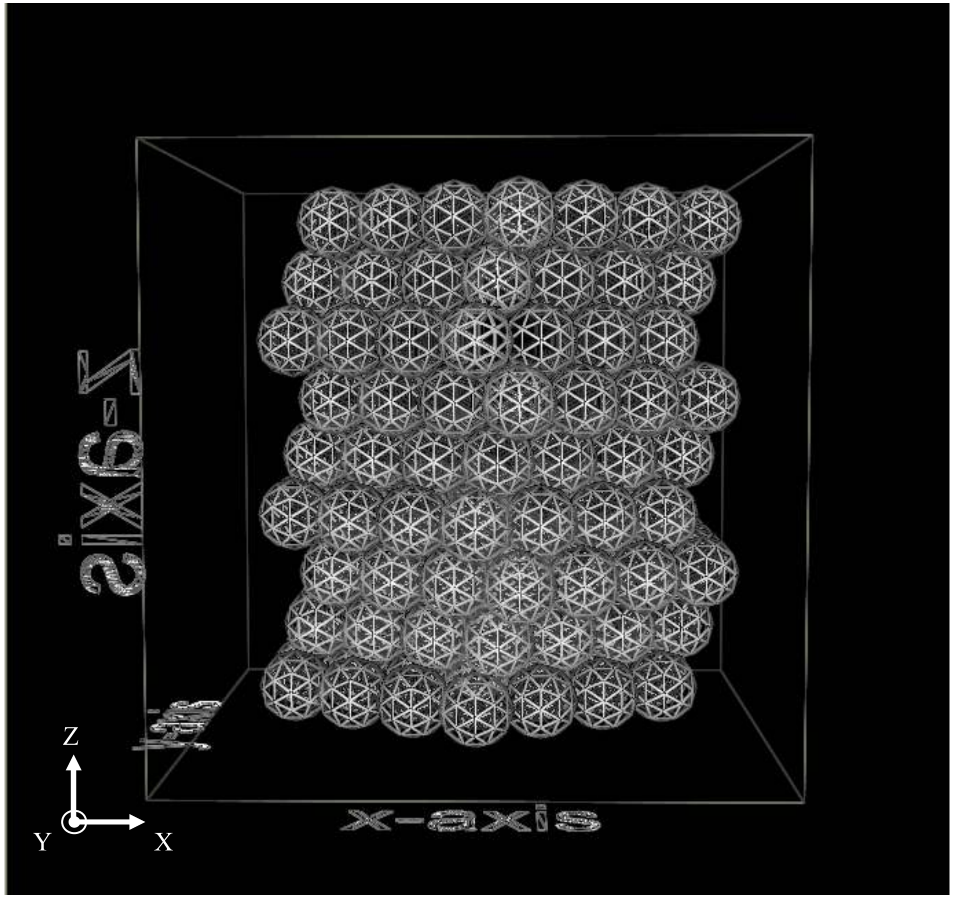
- Improve coupling and reduce losses to achieve phase shift > pi/2
- Establish strong coupling with charged dots.
  - modulation doped
  - electrically charged
- Investigate dynamics of spin via Faraday rotation
  - We cool the spin by measurement
  - Creating spin superposition states (hard)
  - Rotating spin around equator for spin echo (easy=U(φ))
- Spin coherence times (of microseconds?)
- Nuclear ‘calming’ to extend coherence times

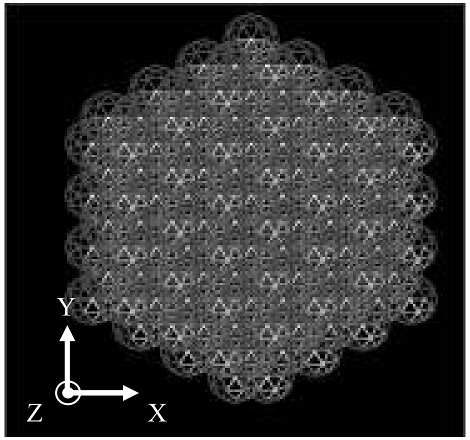
Approaches to 3D cavities

With Daniel Ho

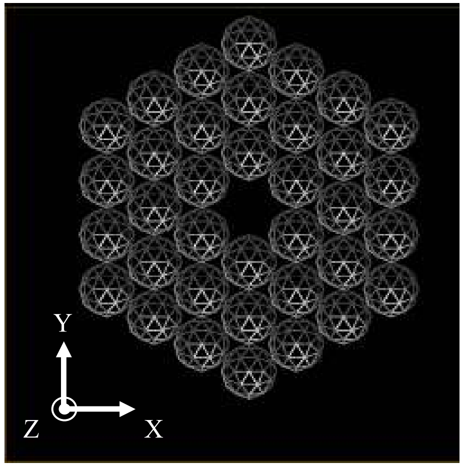
1D Photonic Defect in 3D Inverted Structure

FCC array of spherical holes in Silicon



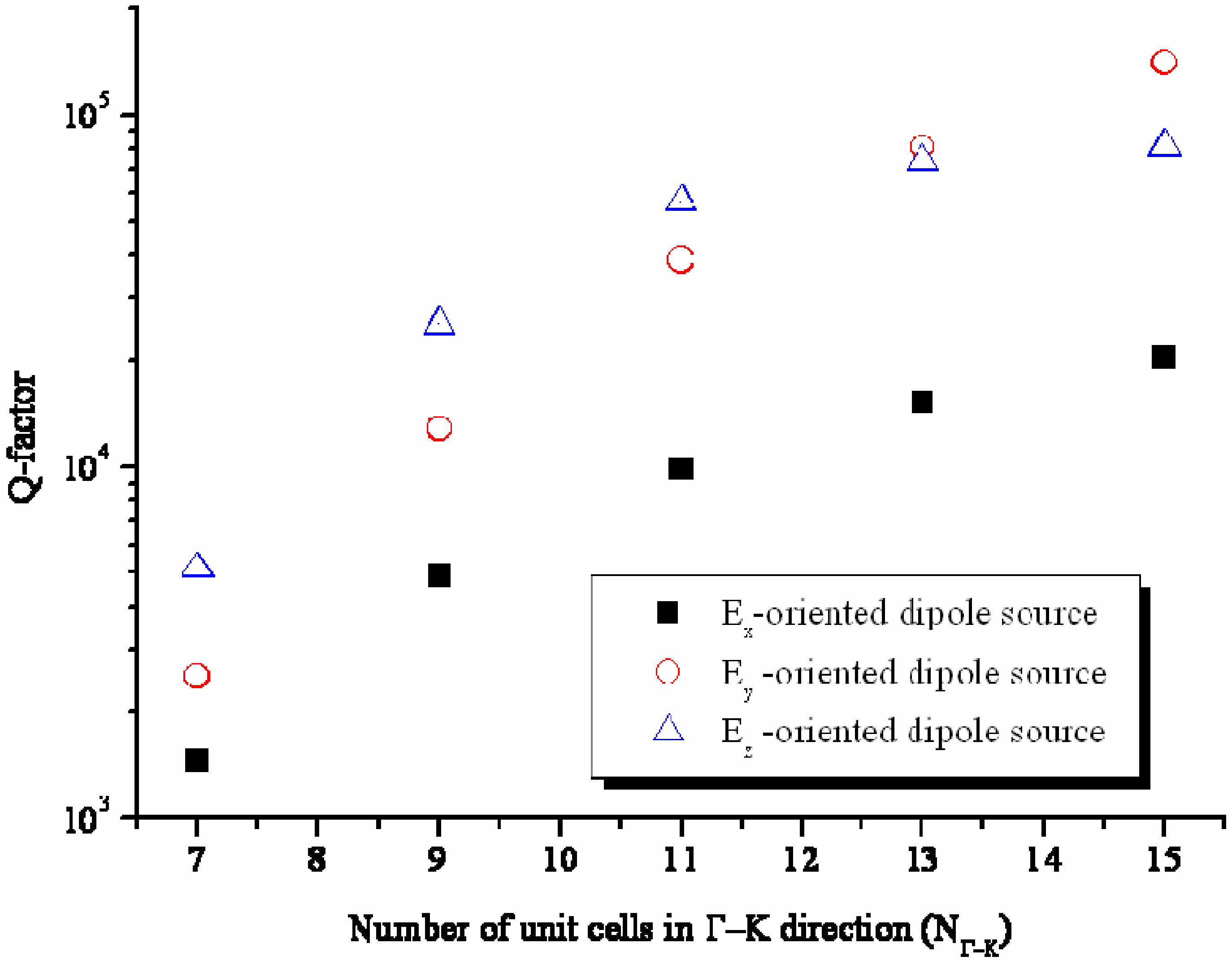


Top view

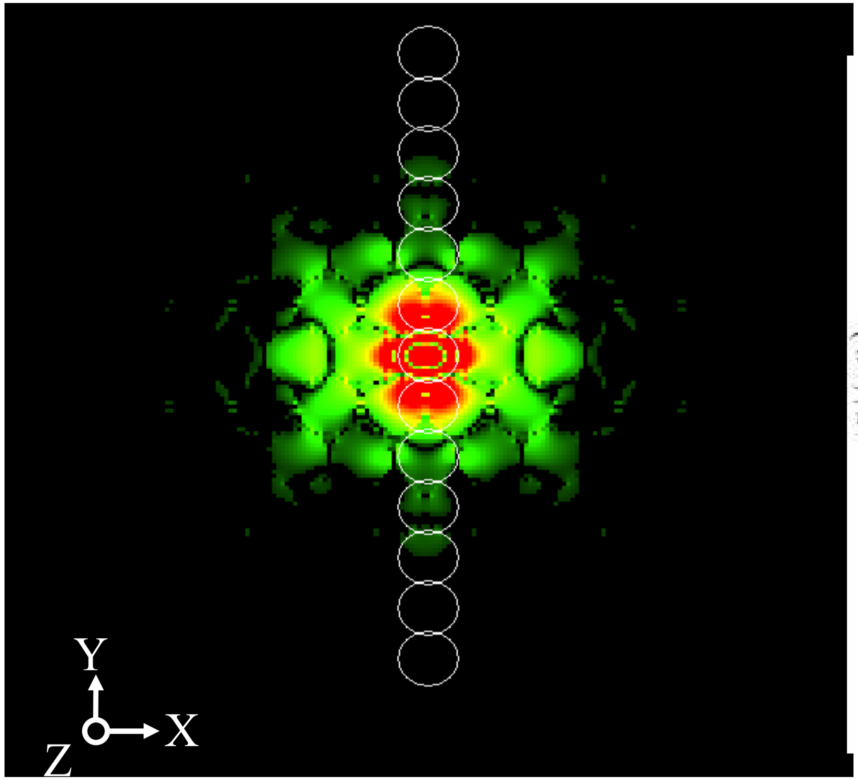


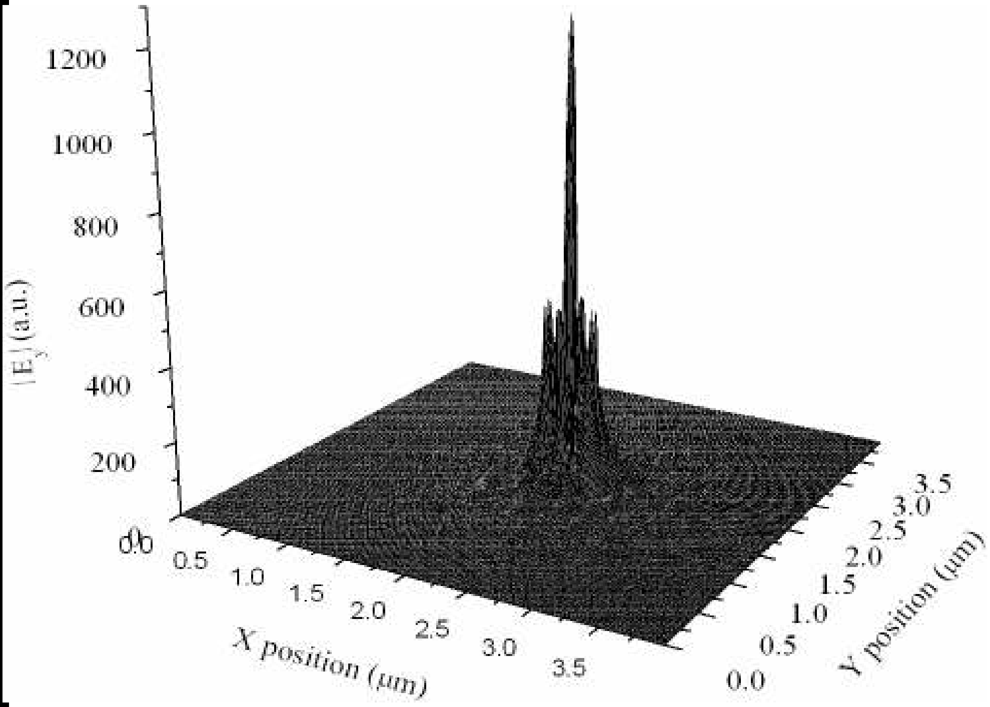
Top view of central 2D Photonic Defect Layer

The finite difference time domain method FDTD



λ res= 536.65 nm, Eymode





Preliminary calculations of cavity volume and Q-factor: inverse FCC in n=3.5 material ‘silicon’.

- $V_{eff} \sim 9e\text{-}5\mu m^3 = 0.19(\lambda/\mathbf{2n})^3$
- Q = 80856
- Q/V = 2.84E8
- $Q/(V)^{0.5} = 4.8E6$

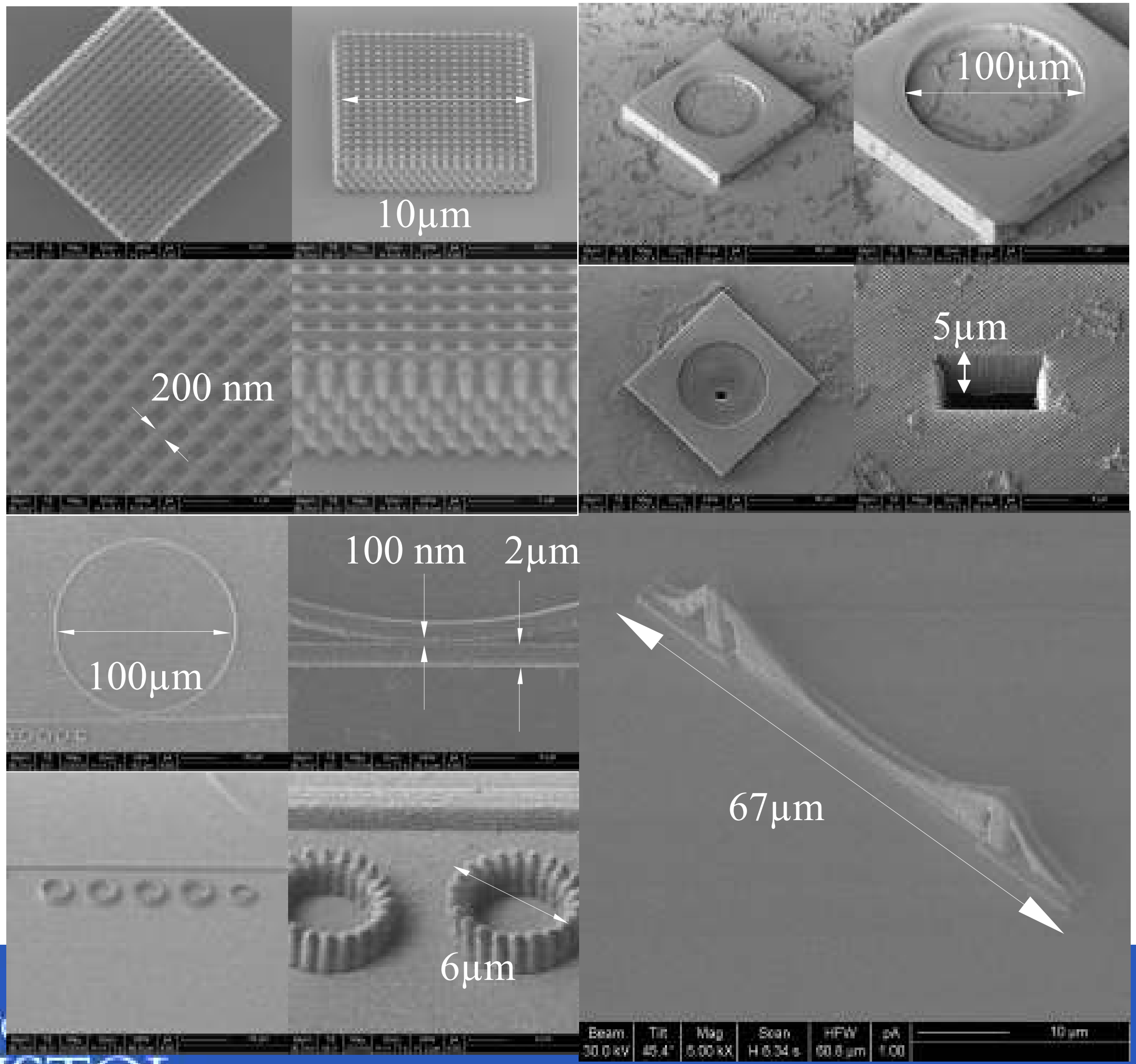
For NV centres

$\kappa/2\pi \sim$ 6 GHz

$\gamma/2\pi \sim$ 3-10 MHz (ZPL)

$g/2\pi \sim$ 20 GHz

3D Two-photon Lithography



Summary and Outlook

- Interaction between light and matter in wavelength scale optical structures
- Quantum dots in nanocavities,
  - 1D systems such as pillar microcavities
- Diamond based microstructures
  - Solid immersion lenses
  - suspended waveguide photonic crystal cavities
- Strong coupling leading to gates
  - Attojoule classical switches
  - Spin photon interface
  - Quantum ‘repeater’
- Modelling 3D systems capable of showing strong coupling