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WINTER COLLEGE
on
QUANTUM AND CLASSICAL ASPECTS
of
INFORMATION OPTICS

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Photonic Quantum Logic

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1-phot

Photonic Quantum Logic

Trieste Winter School 8
FEB 2006

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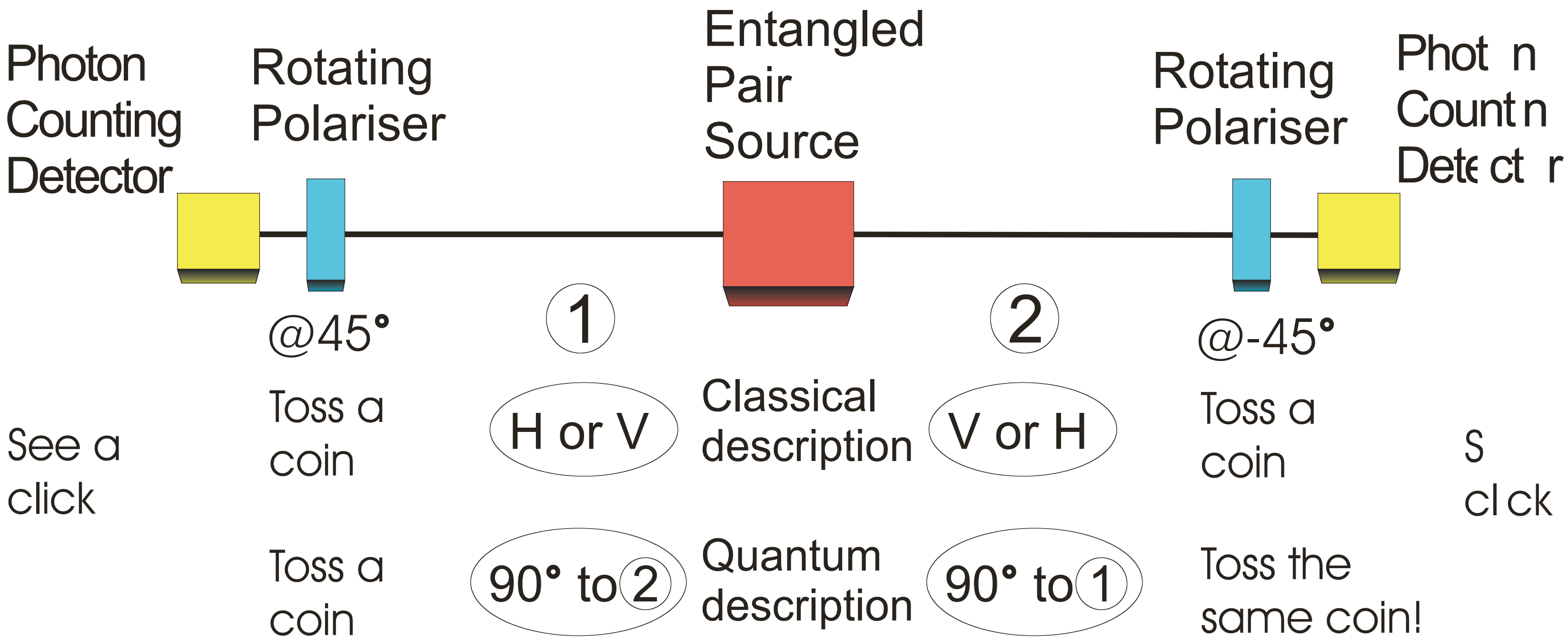
FP6:IP
SECOQC
& QAP

Bristol: Daniel Ho, J. Fulconis, J. Duligall, C. Hu, R. Gibson, O Alibart

Philosophical questions
Non-locality of entangled photon pairs



Rarity: Science Perspective August 2003

Photonic Quantum Information.

- single photon coding for quantum key distribution = a (secure, non-local) random number generator.
- Can we develop more general quantum information processing using quantum effects with photons?

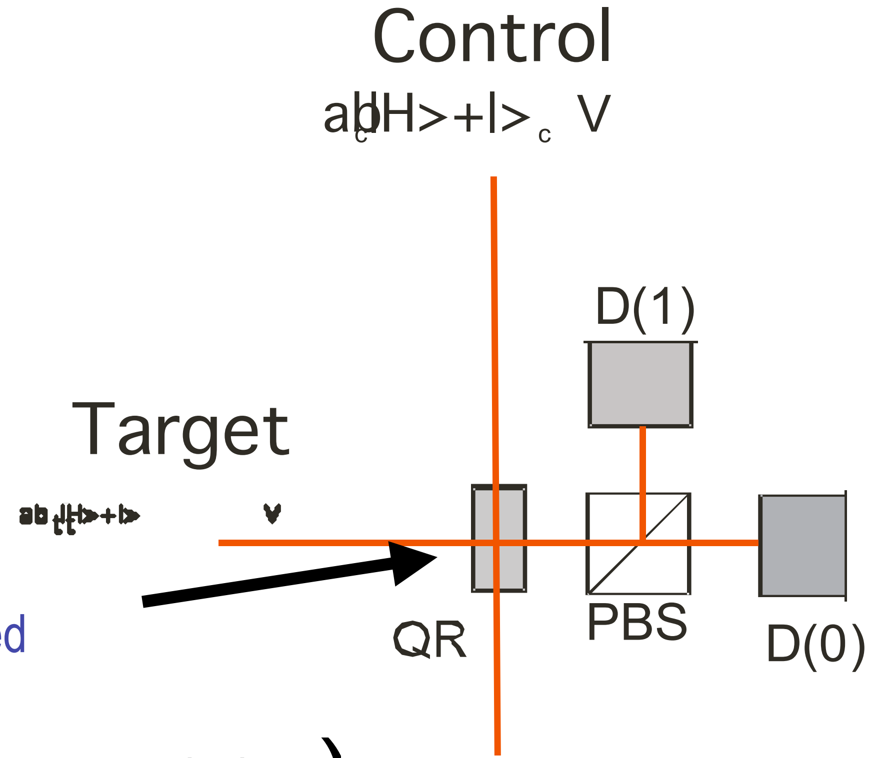
Have:

- low error single qubit manipulation QBER<10^{-4} ,
- Little decoherence (but loss)

Need:

- low error rate and high efficiency controlled NOT gate (**hard**).
- Can we do this with ‘off-the-shelf items’:
- linear optical elements (efficient, scalable?)
- single photon sources (efficiency, pure state?)
- entangled state sources (on demand, pure state?)
- single photon detectors (efficiency, photon number resolving?

2QUBIT logic: Photonic CNOT Gate.



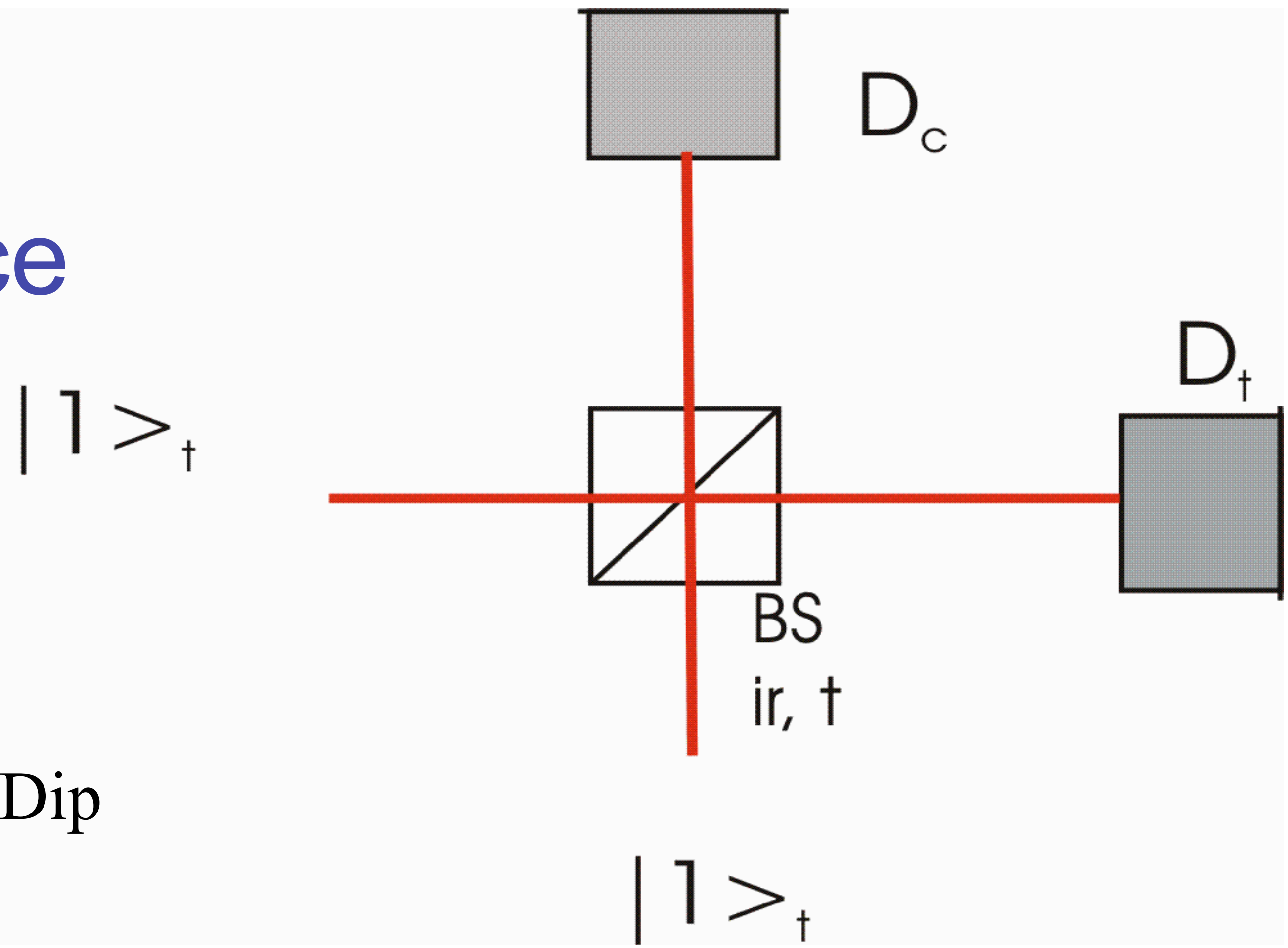
QR is a quantum polarisation rotator
Rotates polarisation if control is vertically polarised
Does nothing if control is Horizontally polarised

$$\left|\Psi\right\rangle_{in} = \left(\alpha\left|0\right\rangle_t + \beta\left|1\right\rangle_t\right)\left(\alpha_c\left|0\right\rangle_c + \beta_c\left|1\right\rangle_c\right)$$

$$\left|\Psi\right\rangle_{out} = \alpha\alpha_c\left|0\right\rangle_t\left|0\right\rangle_c + \alpha\beta_c\left|1\right\rangle_t\left|1\right\rangle_c + \beta\alpha_c\left|1\right\rangle_t\left|0\right\rangle_c + \beta\ \beta_c\left|0\right\rangle_t\left|1\right\rangle_c$$

Requires non-linearity at single photon level:
Atoms: Turchette and Kimble PRL1995,
Solid state: J. P. Reithmaier/ A. Forchel, NATURE 432, Nov 2004.

Hong Ou Mandel interference effect



Hong - Ou - Mandel Dip

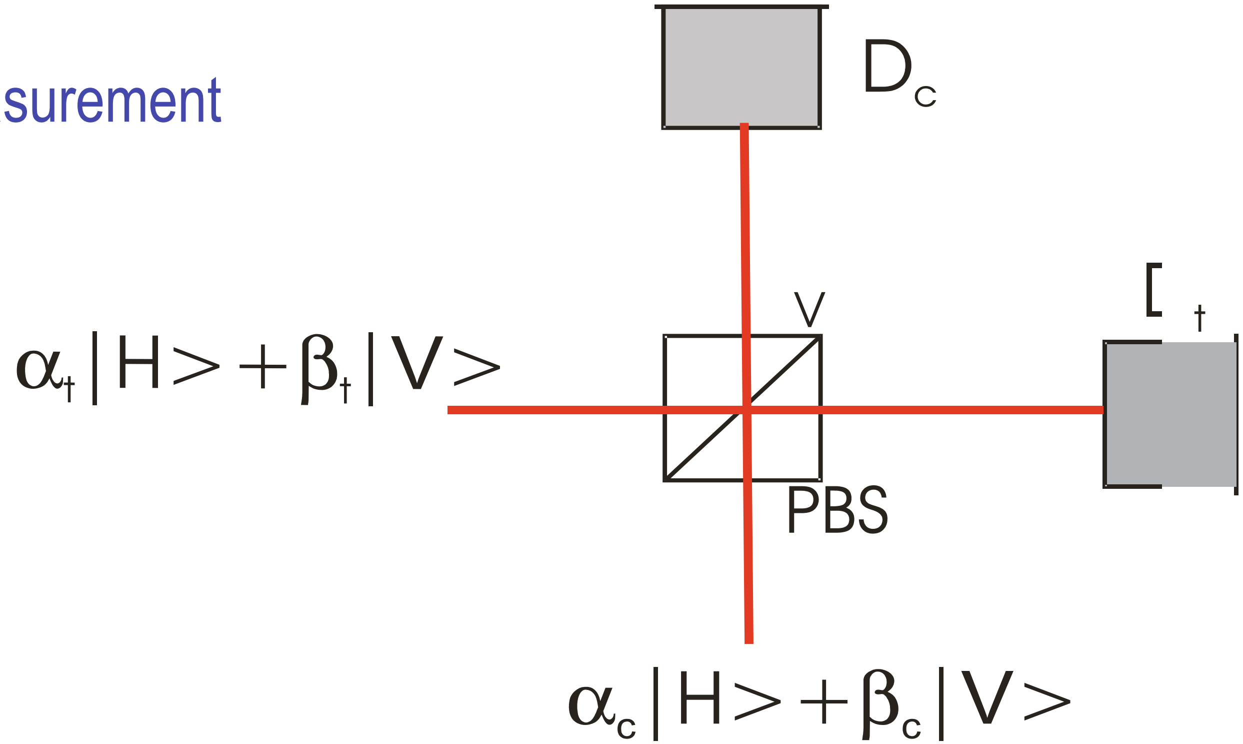
$$|\Psi_{in}\rangle = |1\rangle_t |1\rangle_c$$

$$|1\rangle_t \rightarrow t|1\rangle_t + ir|1\rangle_c : |1\rangle_c \rightarrow t|1\rangle_c + ir|1\rangle_t$$

$$|\Psi_{out}\rangle = \left((t^2 - r^2)|1\rangle_t |1\rangle_c + irt|1,1\rangle_t + irt|1,1\rangle_c\right)$$

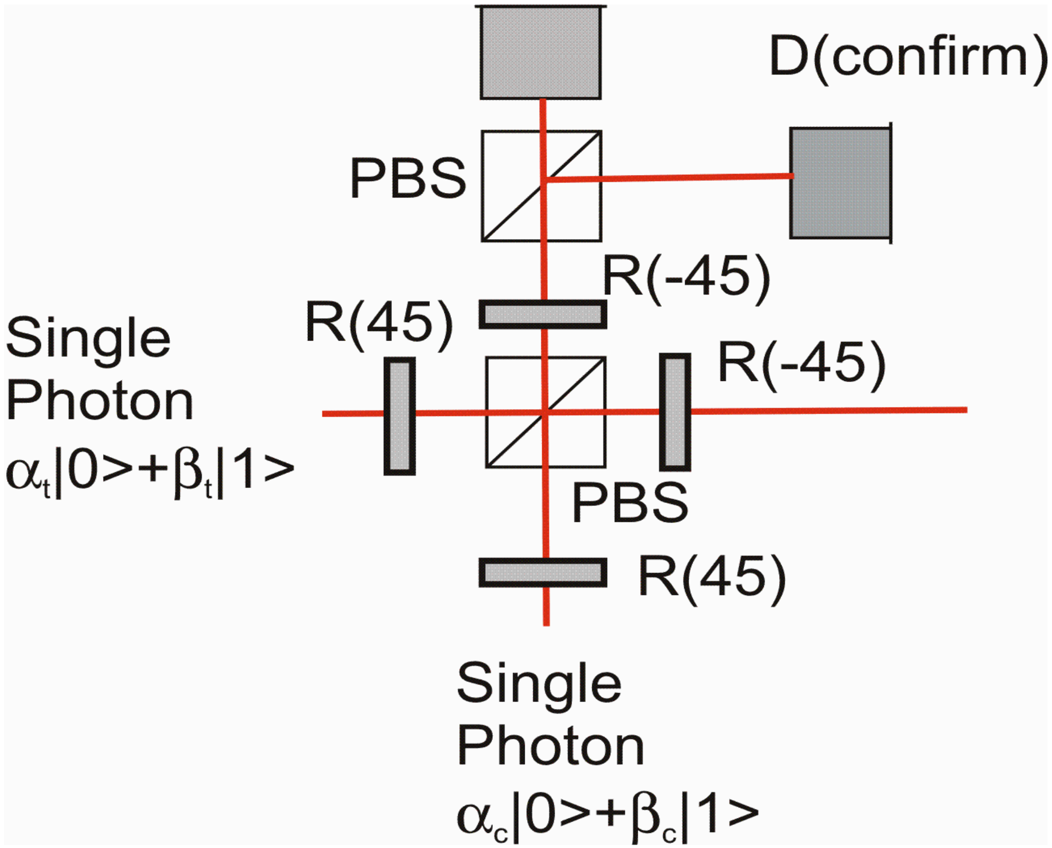
Hong, Ou, Mandel
PRL 1987

Parity Measurement



Linear conditional CNOT gate

Knill et al Nature 409, 46–52 (2001)
Pittman et al (2002) PRL 88, 257902



Not 100% efficient but
Up to 50%

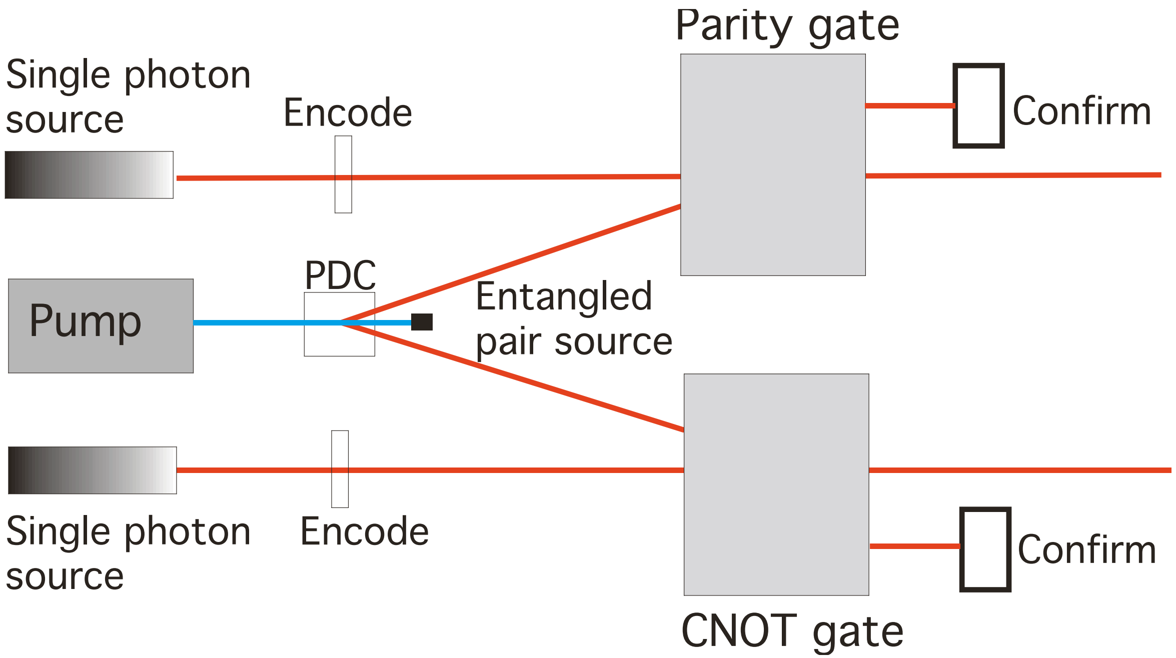
Notes

Target V-->H+V Control V-->H+V
Parity-->HH+VV -45--> H(H+V)-V(H-V)
Confirm click is H-->(H-V) out -45--> |H>
Confirm click is V-->(H+V) out -45--> |V>

Target V-->H+V Control H-->H-V
Parity-->HH-VV -45--> H(H+V)+V(H-V)
Confirm click is H-->(H+V) out -45--> |V>

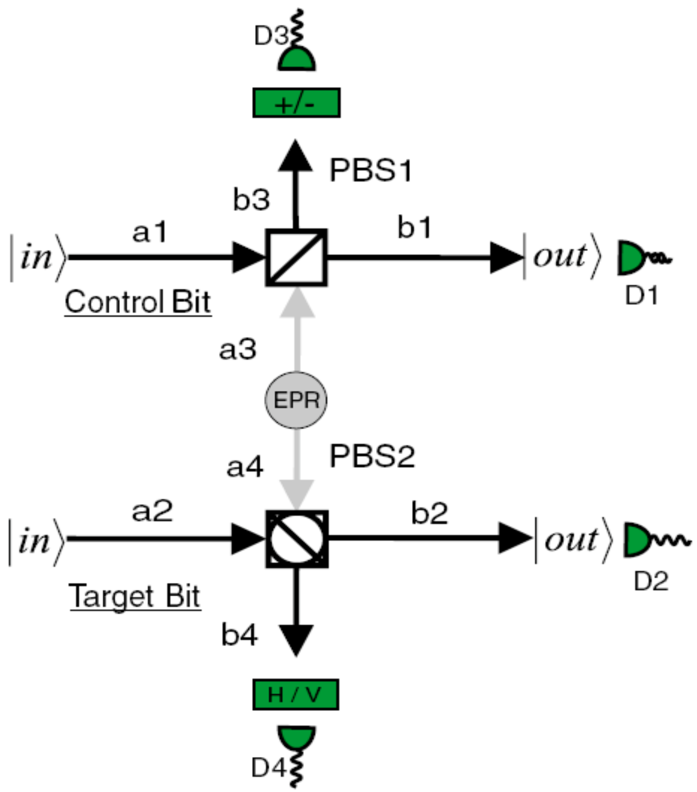
Possible Scalable gate?

Franson et al 2003
Zeilinger et al 2004

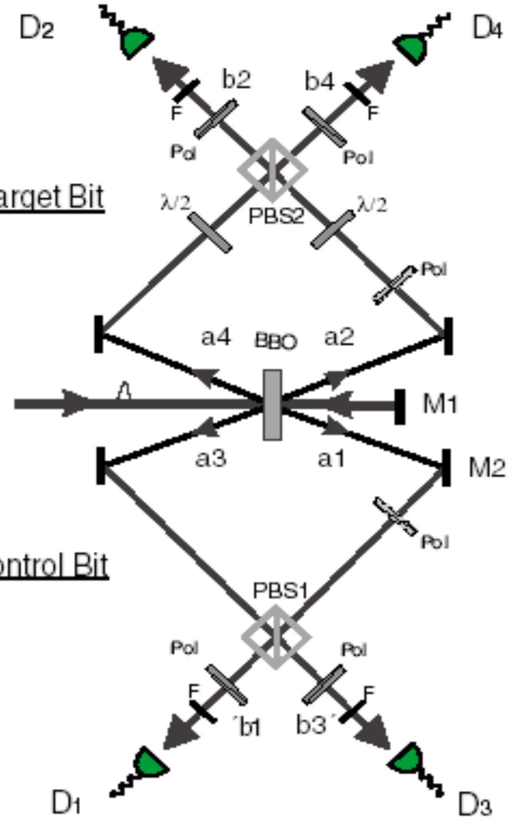


Using teleportation to make non-destructive gates

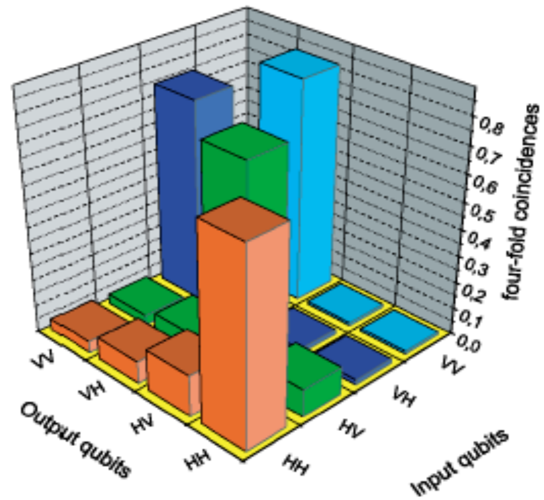
A ‘scalable’ 2-qubit CNOT gate



In the proposal



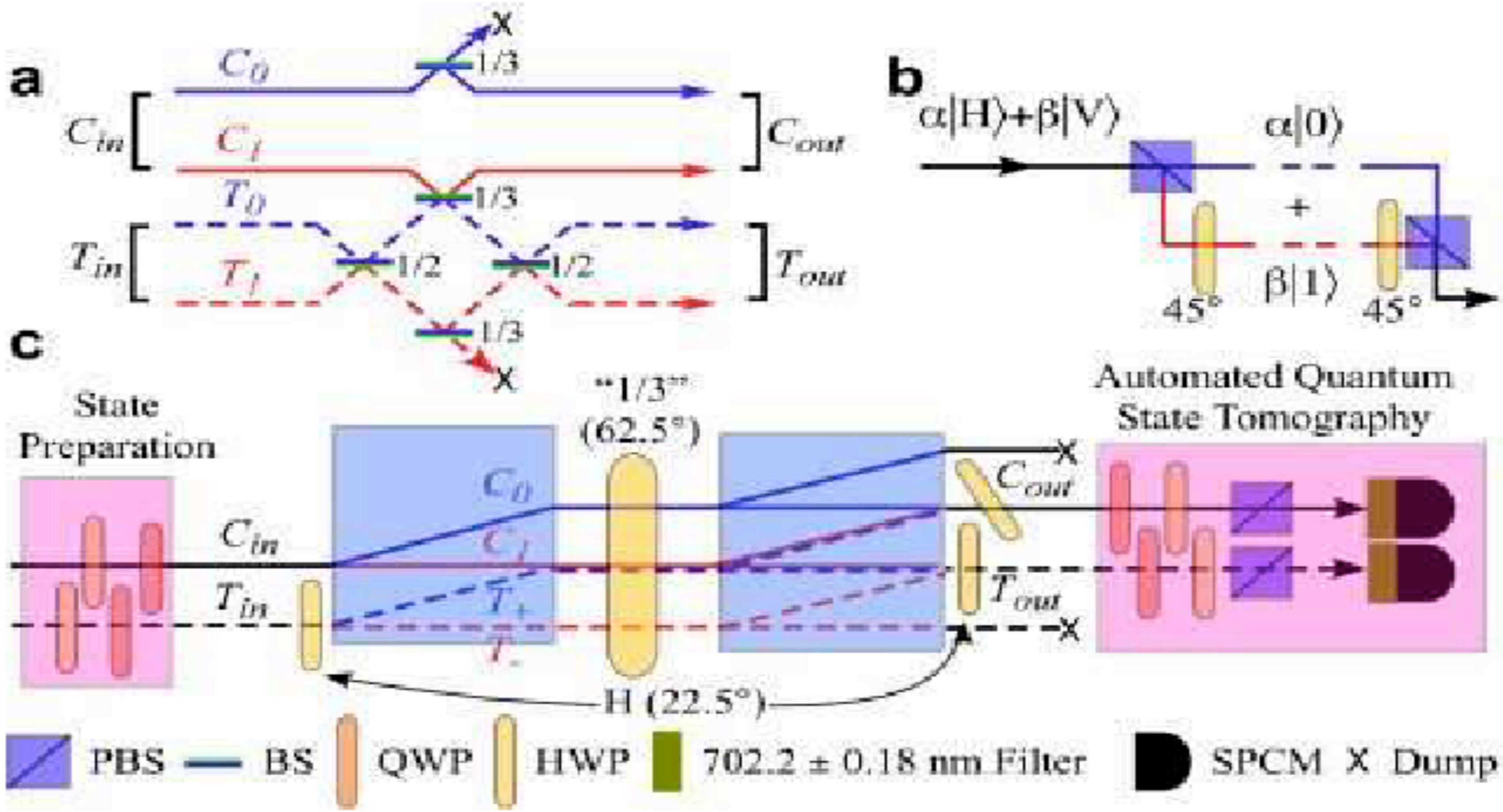
Actual realisation



Truth table
Fidelity ~0.8

S. Gasparoni, J-W Pan, P. Walther, T. Rudolph, and A. Zeilinger, Phys. Rev. Lett. **93**, 020504 (2004)

Demonstration of an all-optical quantum controlled-NOT gate

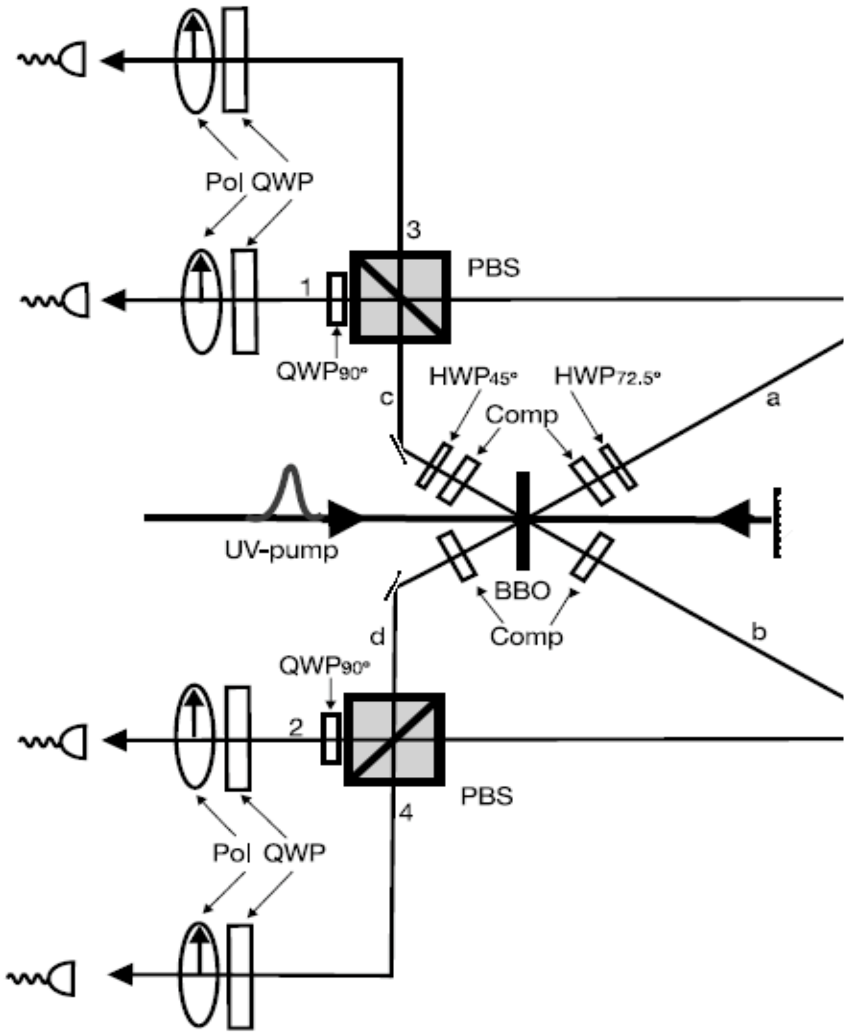


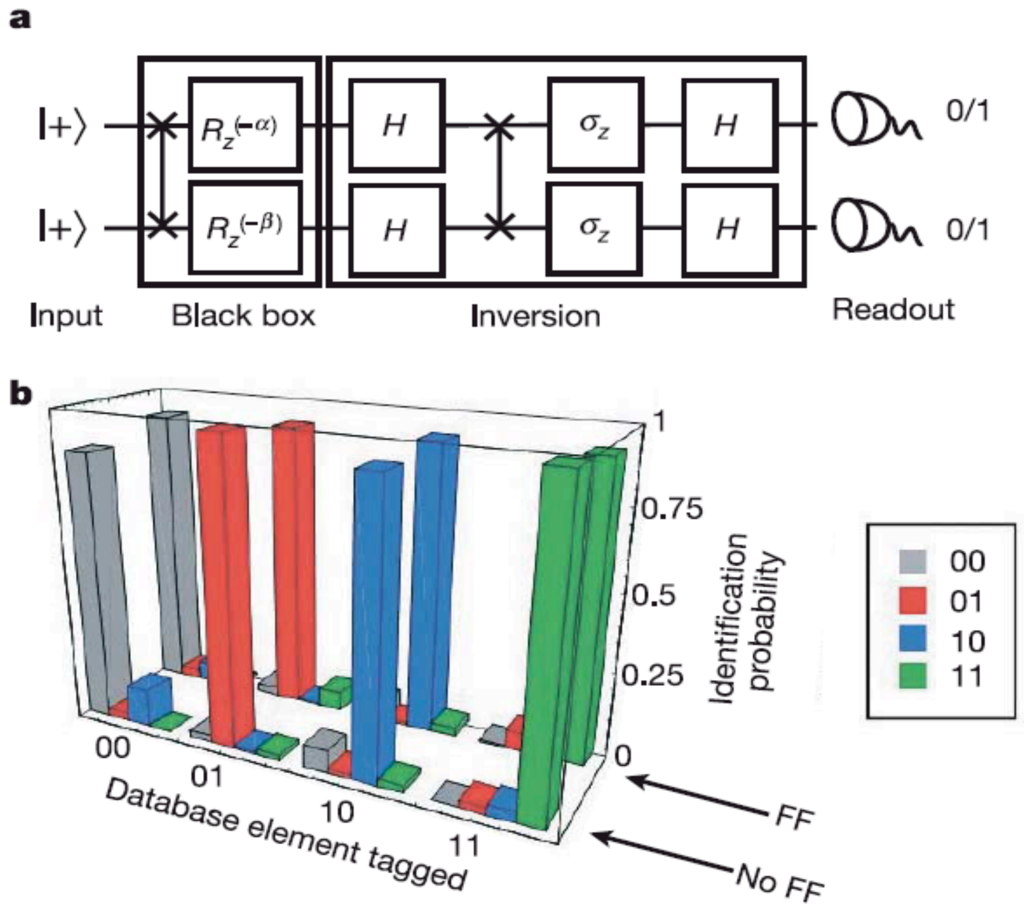
Knill et al Nature 409, 46–52 (2001)

J L O'Brien et al, ***Nature* 426,** 264 (2003) / quant-ph/0403062

Optical Cluster State Computing

P. Walther et al Nature **434**, 169-176 (2005)





Futures of optical quantum logic

- Higher numbers of entangled photons 6-fold entanglement in view
- Still require efficiency improvements in deterministic sources and detectors
- Weakly non-linear gates with enhanced efficiency and scalability
- Fully non-linear gates

Strong coupling of a single QD in 3D microcavity

Cavity Quantum Electrodynamics (CQED)

Coupling of QD with Cavity $$g = \sqrt{\frac{1}{V_{eff}} \frac{\hbar^2}{4\pi\varepsilon_r\varepsilon_0} \frac{\pi e^2 f}{m}}$$

Oscillator Strength $$f = \frac{\left|\left\langle \Psi_{ex} \middle| \hat{e} \cdot \hat{P} \middle| 0 \right\rangle\right|^2}{m\hbar\omega / 2} \approx 10 - 50$$ for Q-dots

Broadening of QD emission γ_e: dephasing time and lifetime

Broadening of cavity mode $$\gamma_c = \frac{h\upsilon}{Q}$$

Cavity Quantum Electrodynamics (CQED)

Mixed states of QD and photon

$$E_{\pm} = E_0 - i\frac{\gamma_e + \gamma_c}{4} \pm \sqrt{g^2 - \left(\frac{\gamma_e - \gamma_c}{4}\right)^2}$$

- Strong coupling ($g > |\gamma_c - \gamma_e|/4$)

Rabi oscillations — reversible spontaneous emission

Rabi splitting $\hbar\Omega = 2\sqrt{g^2 - \left(\frac{\gamma_e - \gamma_c}{4}\right)^2}$

Applications in QIP

Single-photon switch

Exciton-photon entanglement

Micro-pillar: Nature 432, 197(2004)

PhC cavity: Nature 432, 200(2004)

Microdisk: PRL 95, 067401(2005)

Cavity Quantum Electrodynamics (CQED)

- Weak coupling ($g < |\gamma_c - \gamma_e|/4$)

Enhanced spontaneous emission

$$\frac{\tau_{free}}{\tau_{cavity}} = \frac{3Q(\lambda/n)^3}{4\pi^2 V_{eff}} \frac{\Delta\omega_c^{\ 2}}{4(\omega_e - \omega_c)^2 + \Delta\omega_c^{\ 2}} \frac{\left|\vec{E}(\vec{r})\right|^2}{\left|\vec{E}_{\max}\right|^2} \left(\frac{\vec{d} \cdot \vec{E}(\vec{r})}{\left|\vec{d}\right| \left|\vec{E}(\vec{r})\right|} \right)^2$$

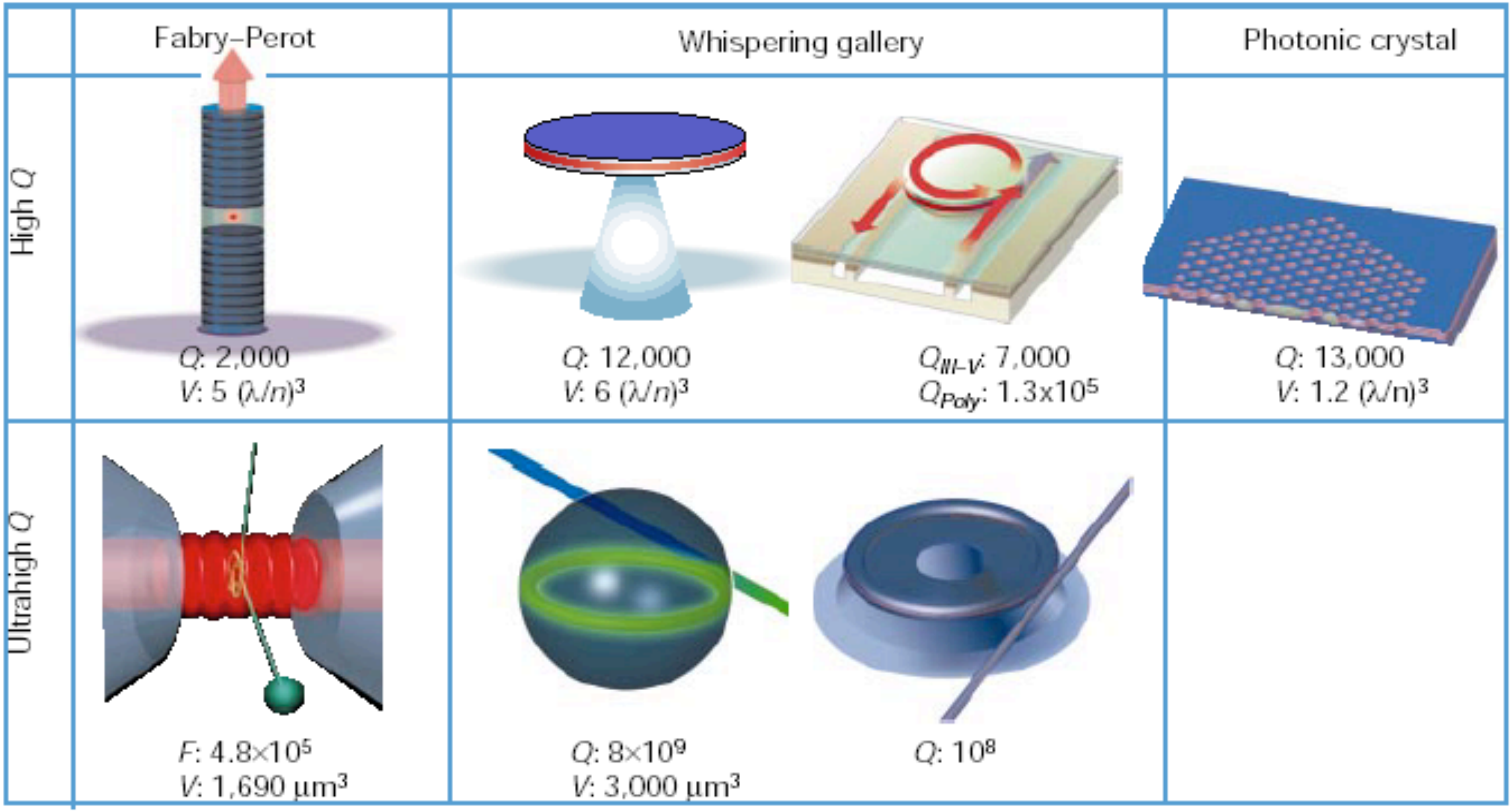
Purcell factor F_p — detuning — position — orientation

Large $\frac{Q}{V_{eff}}$ → large F_p

Improve efficiency of light emitter

Typical 3D Optical Microcavities

K.J. Vahala, Nature 424, 839 (2003)

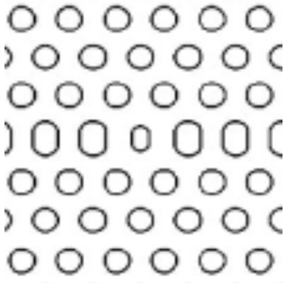


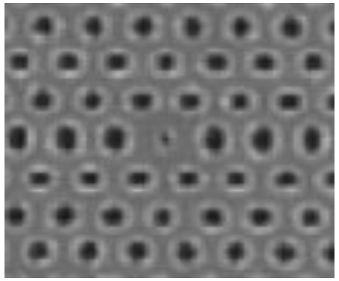
Theoretical limit of modal volume ~ $0.125\times(\lambda/n)^3$

PhC Slab Cavities: *Q* vs. *V*

Taken from Johnson's lecture LEOS-05

[Loncar, *APL* **81**, 2680 (2002)]



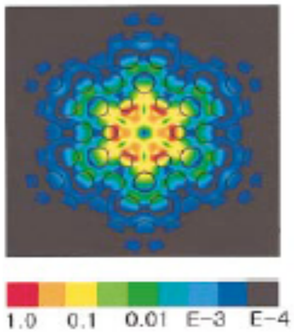


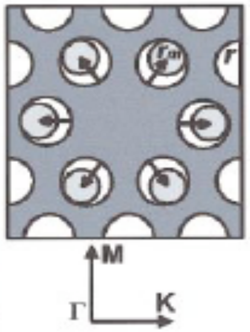
H1

$Q \sim 10{,}000$ ($V \sim 4 \times$ optimum)

$= (\lambda/2n)^3$

[Ryu, *Opt. Lett.* **28**, 2390 (2003)]



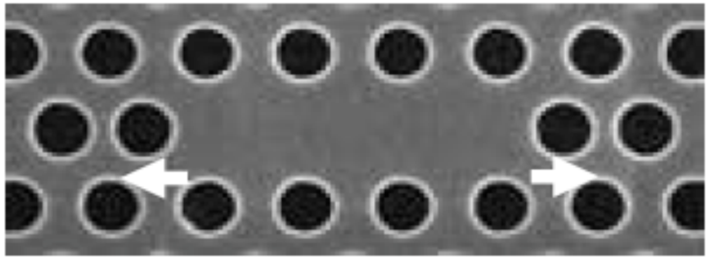


H1

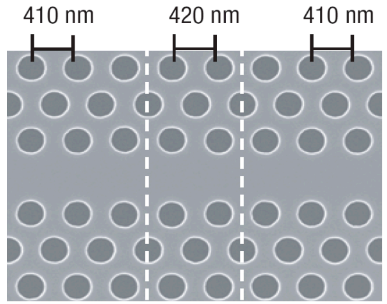
$Q \sim 10^6$ ($V \sim 11 \times$ optimum)

[Akahane, *Nature* **425**, 944 (2003)]

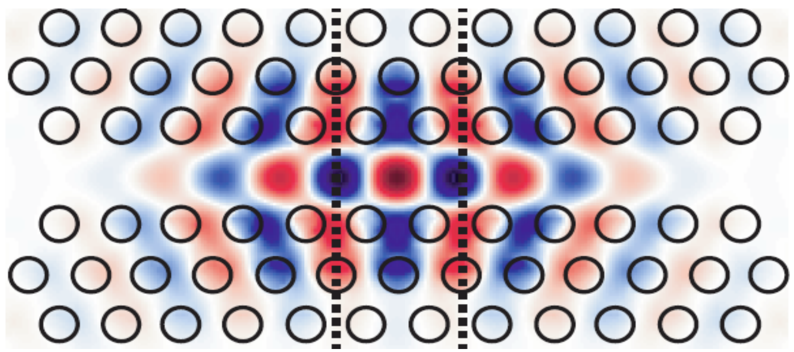
L3



$Q \sim 45{,}000$ ($V \sim 6 \times$ optimum)

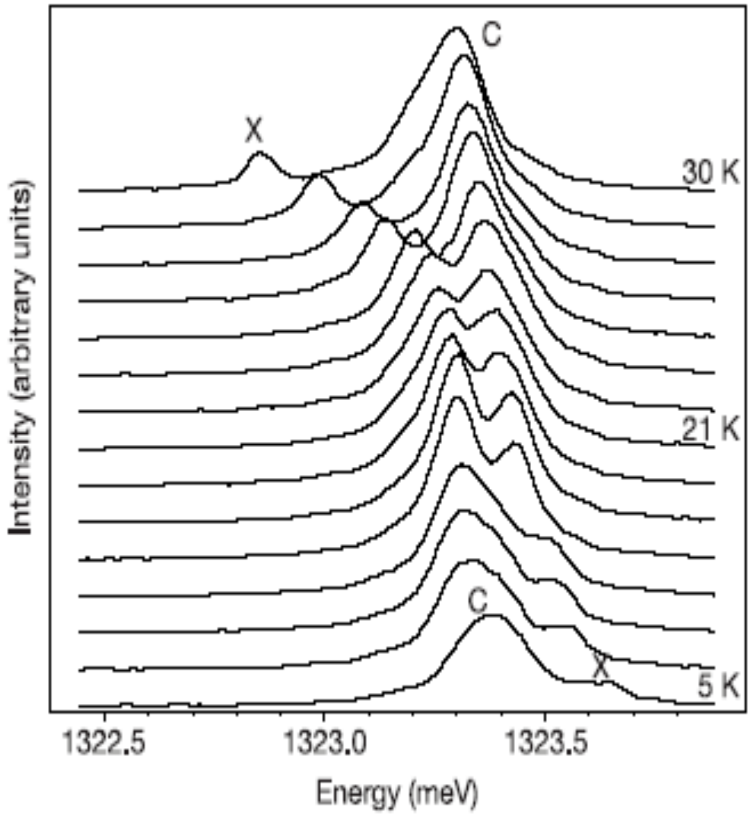


[Song, *Nature Mat.* **4**, 207 (2005)]



$Q \sim 600{,}000$ ($V \sim 10 \times$ optimum)

Forchel's group



QD: $In_{0.3}Ga_{0.7}As$ QD of size 100nm×30nm

Oscillator strength: f=50

Fabrication: circular micropillars by ICP

Pillar size: d_c =1.5 μm with maximal Q/d_c selected

Q-factor: 8800

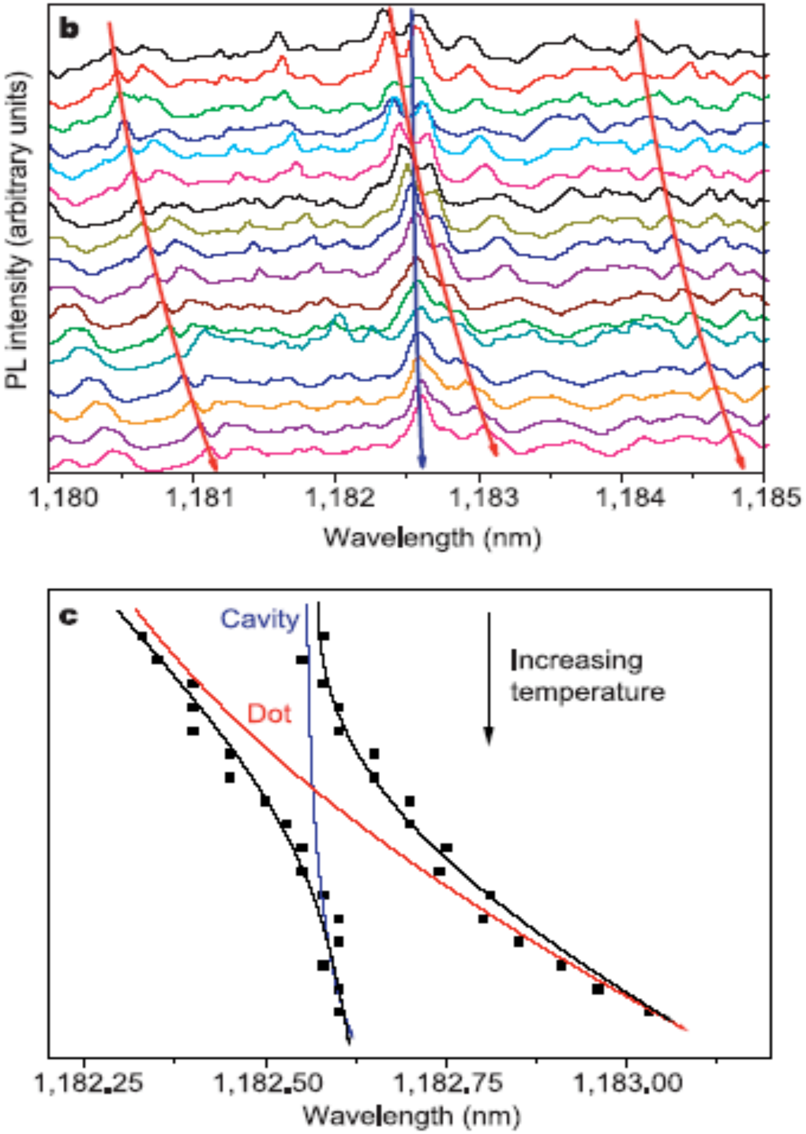
Mode volume: 0.3 μm^3

Coupling constant: g=0.08 meV

Vacuum Rabi splitting: hΩ=0.14 meV

Nature 432, 197(2004)

Scherer's group



QD: conventional InAs QD, oscillator strength f=10

Fabrication: photonic crystal defect cavity by ICP

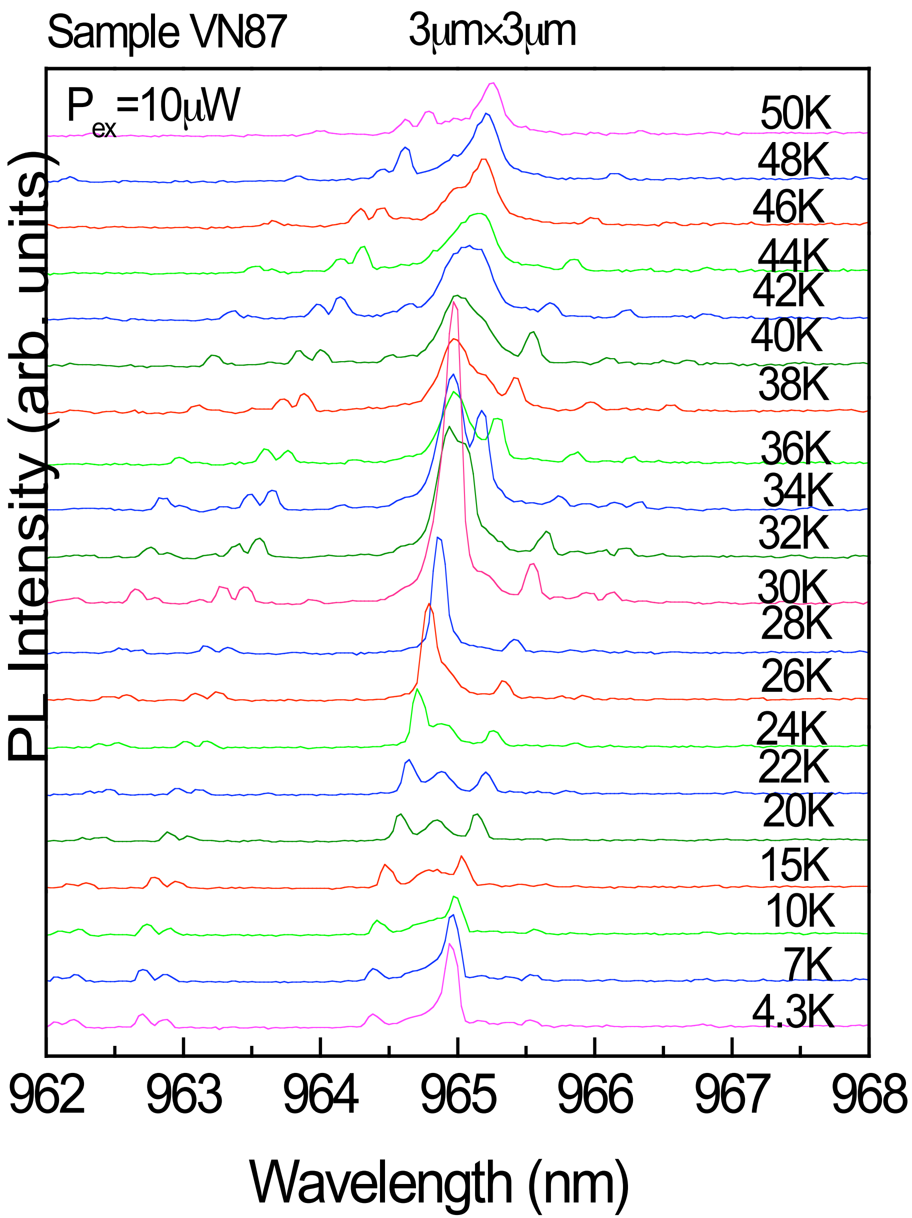
Q-factor: 13,300

Mode volume: 0.04 μm^3

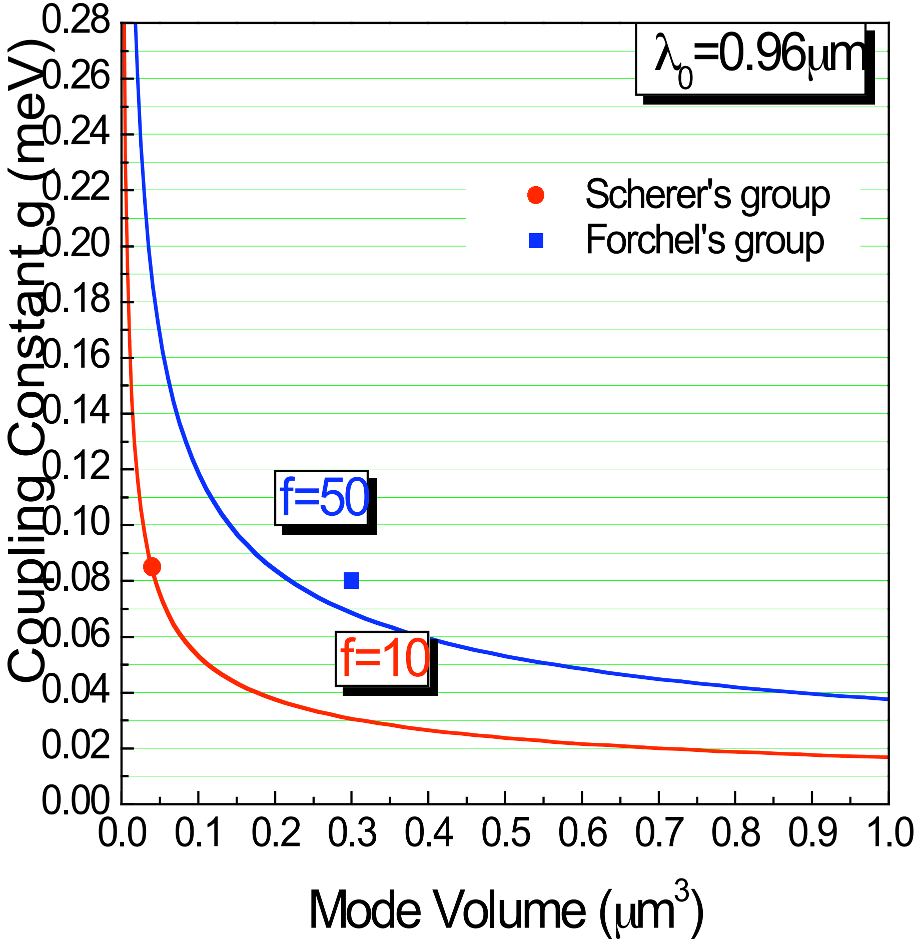
Coupling constant: g=0.085 meV

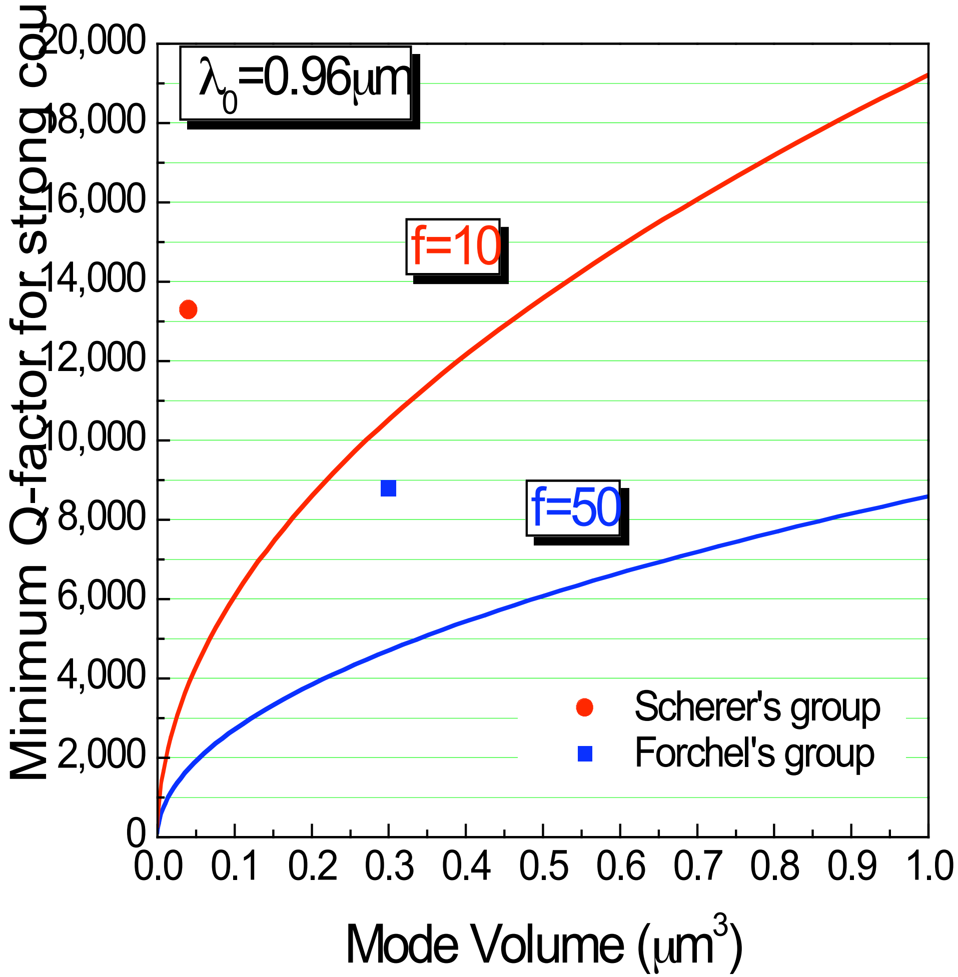
Vacuum Rabi splitting: hΩ=0.17 meV

Nature 432, 200(2004)



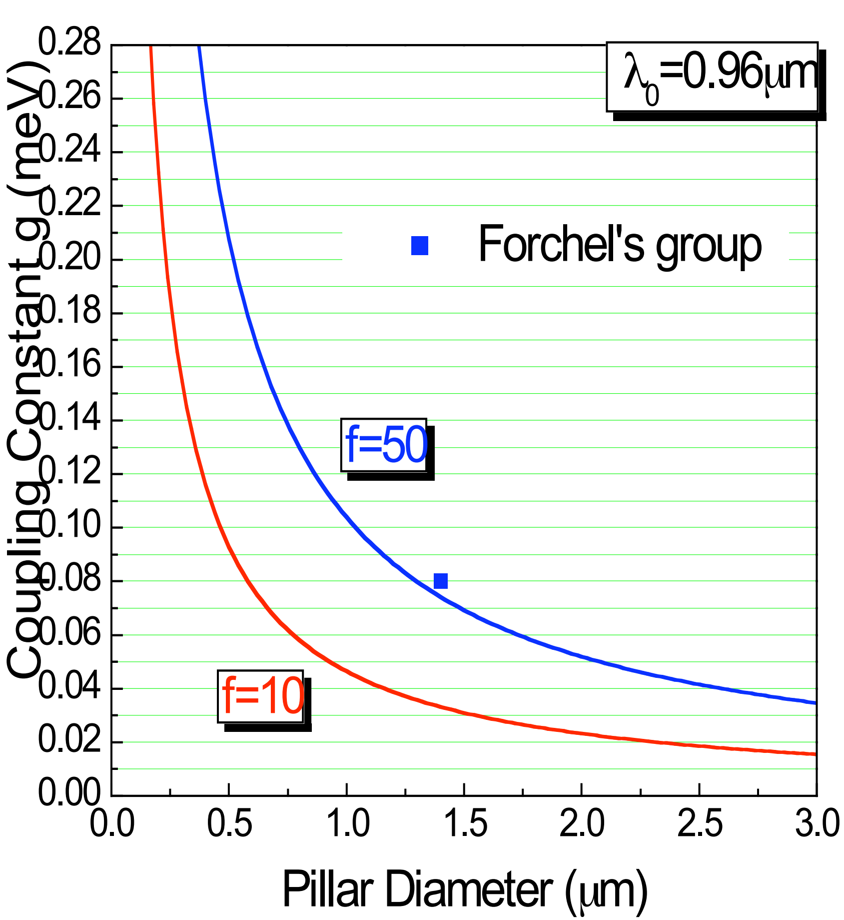
Sample VN87
3μm×3μm
P_{ex}=10μW
50K
48K
46K
44K
42K
40K
38K
36K
34K
32K
30K
28K
26K
24K
22K
20K
15K
10K
7K
4.3K
PL Intensity (arb. units)
962
963
964
965
966
967
968
Wavelength (nm)

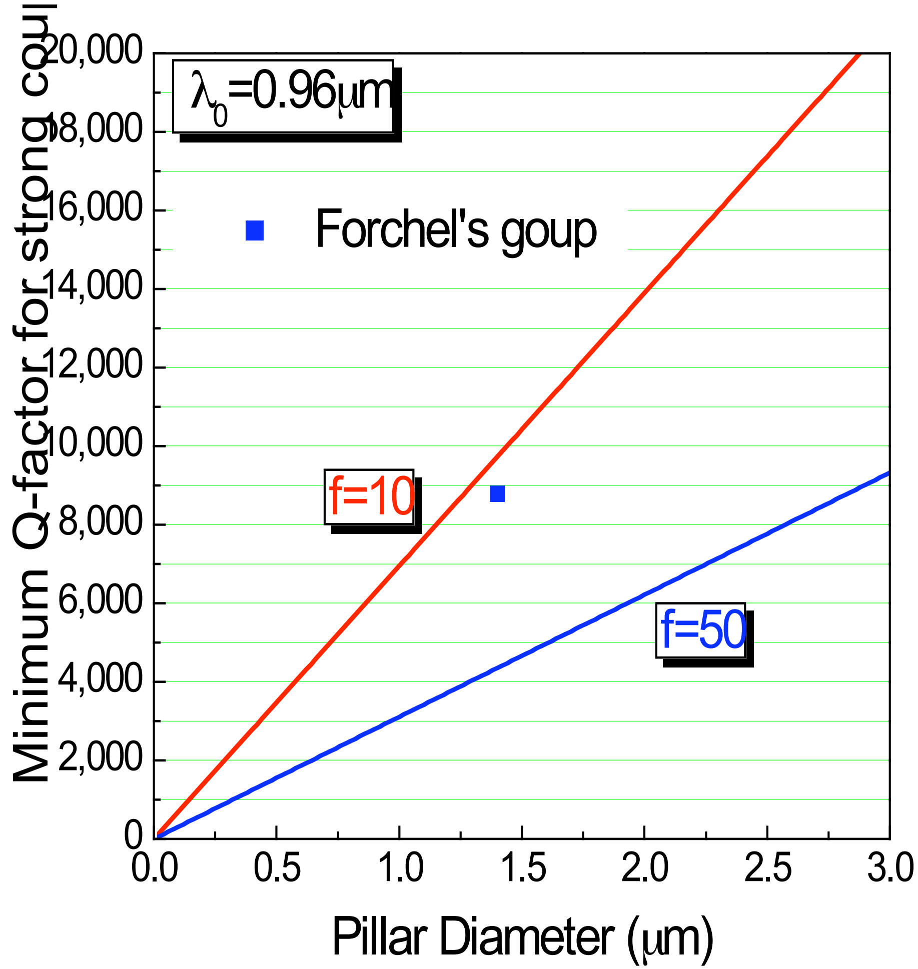




Condition for strong coupling: $g > \Delta\omega_c/4 \Leftrightarrow Q > \omega/4g$

Condition for resolved vacuum Rabi splitting: $g > 0.05$ meV





Condition for strong coupling: g $>\Delta\omega_c/4 \Leftrightarrow$ Q > $\omega/4g$

Condition for resolved vacuum Rabi splitting: g > 0.05 meV

Challenges for strong coupling of single QD

For smaller InAs QD with f=10

1. Micropillars with diameter < 0.9 μm, Q factor >8000
2. Photonic crystal cavity with mode volume < 0.1 μm^3, Q factor >8000

For larger InGaAs QD with f=50

3. Micropillars with diameter < 2.0 μm, Q factor >6000
4. Photonic crystal cavity with mode volume < 0.5 μm^3, Q factor >6000

other conditions:

QD situated at the field maxima of mode

to inclease oscillator strength by increasing coherence volume of exciton

QD with large size (f~50)

interface bound exciton (f~100)

bound exciton