Quantum Optics in Wavelength Scale Structures

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Confining light: periodic dielectric structures

Photonic crystals

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

Particle like
Wave-like during propagation
Particle like

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

~5% collection into 0.9NA lens from flat surface

~30% collection into SIL + 0.9NA lens

FDTD simulation
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**

\[ \gamma \]

- QD dipole decay rate \[ \kappa + \kappa_s = \frac{\omega}{Q} = \frac{1}{\tau} \]

- Cavity decay rate \[ g \ll \kappa + \kappa_s, \gamma \]

- Weak cavity coupling

\[ \eta \sim \frac{\kappa}{\kappa + \kappa_s} \]

- Efficiency

\[ P \sim 1 + \frac{3Q\left(\frac{\lambda}{n}\right)^3}{4\pi^2V_{\text{eff}}} \]

- Purcell Factor

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[University of Bristol logo]
FDTD simulations: 0.50 µm

![Graph showing efficiency and Q-factor as functions of the number of top mirror pairs (Nt). Efficiency decreases while Q-factor increases with increasing Nt.]

- Efficiency (%)
- Q-factor
- Number of top mirror pairs (Nt)

0 10 20 30 40 50 60 70 80 90 100
0 1500 3000 4500 6000 7500 9000 10500 12000

12 13 14 15 16 17 18 19 20
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

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)

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.

Hybrid QIP
The PROBLEM: many qubits quantum processor

\[ \eta_s^N, \eta_g^N, F^N, \eta_d^N \]

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

Unitary transform
Linear gates \( \eta < 0.5 \ F > 0.99 \)
Non-linear optics \( \eta \approx 1 \ F > 0.9 ? \)

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

Throughput~ \[ \eta_s^N \eta_d^N \eta_g^N \cdot f(F) \cdot R \]
Spin photon interface using charged quantum dots in microcavities

Cavity Quantum Electrodynamics (CQED)

QD-cavity interaction

\[
g = \sqrt{\frac{\hbar^2}{4\pi\varepsilon_r\varepsilon_0} \frac{\pi e^2 f}{m V_{\text{eff}}}}
\]

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

QD dipole decay rate \( \gamma \)

Cavity decay rate

\[
\kappa + \kappa_s = \frac{\hbar \omega}{Q}
\]

Strong coupling

\[
g > \frac{\kappa + \kappa_s}{4}
\]

To optimise \( g/\kappa \)

Maximise \( Q/V^{1/2} \)
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

\[
\begin{align*}
(a) & \quad a_{\text{in}} \quad a_{\text{out}} \\
(b) & \quad \text{Charged Exciton } X^- \\
& \quad \sigma^+ \quad \sigma^- \\
& \quad \text{(L-light)} \quad \text{(R-light)}
\end{align*}
\]

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 \( g \gg \kappa, \gamma \quad r(\omega \sim \omega_c) = 1 \)

Phase shift gate

\[
\hat{U}(\Delta \varphi) = e^{i\Delta \varphi (|L\rangle\langle L| \otimes |\uparrow\rangle\langle \uparrow| + |R\rangle\langle R| \otimes |\downarrow\rangle\langle \downarrow|)}
\]
Giant optical Faraday rotation

- Electron spin $\uparrow$, L-light feels a hot cavity and R-light feels a cold cavity
- Electron spin $\downarrow$, R-light feels a hot cavity and L-light feels a cold cavity
- By suitable detuning can arrange orthogonal, Giant Faraday rotation angle

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

Achievable with

$$\frac{g}{(\kappa + \kappa_s)} > 0.1 \quad \frac{\kappa}{\kappa_s} \sim 1 \quad \text{Low efficiency}$$

$$\frac{g}{(\kappa + \kappa_s)} > 1.5 \quad \frac{\kappa}{\kappa_s} >> 1 \quad \text{High efficiency}$$
Quantum non-demolition detection of a single electron spin

Input light

\[ |H\rangle = \frac{1}{\sqrt{2}} (|R\rangle + |L\rangle) \]

Spin up

\[ |H\rangle \otimes |\uparrow\rangle \xrightarrow{\hat{U}(\pi/2)} \frac{1}{\sqrt{2}} |45^0\rangle |\uparrow\rangle \]

Spin down

\[ |H\rangle \otimes |\downarrow\rangle \xrightarrow{\hat{U}(\pi/2)} \frac{1}{\sqrt{2}} |45^0\rangle |\downarrow\rangle \]

Spin superposition state

\[ \alpha |\uparrow\rangle + \beta |\downarrow\rangle \]

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


A photon spin entangler!
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](https://arxiv.org/abs/1005.5545)

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

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

<table>
<thead>
<tr>
<th>Photons 1, 2</th>
<th>Spin</th>
<th>Photon 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>H\rangle_1</td>
<td>H\rangle_2 \text{ or }</td>
</tr>
<tr>
<td>(</td>
<td>H\rangle_1</td>
<td>V\rangle_2 \text{ or }</td>
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</tbody>
</table>
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

\[ r(\omega) = |r(\omega)| e^{i\phi} \]

\[ = 1 - \frac{\kappa (i(\omega_{qd} - \omega) + \frac{\gamma}{2})}{(i(\omega_{qd} - \omega) + \frac{\gamma}{2})(i(\omega_c - \omega) + \frac{\kappa}{2} + \frac{\kappa_s}{2}) + g^2} \]
Resonant reflection spectra of an empty 4µ pillar (Q~84000)
Strongly coupled cavity on resonance
Resonant reflection spectra of a 2.5µm 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

\[\Delta \phi \approx 0.05 \text{ rad (0.12 rad)}\]

\[g \approx 9.4 \text{ueV} \quad \kappa + \kappa_s \approx 26 \text{ueV} \quad \gamma \approx 5 \text{ueV}\]

\[g > \frac{(\kappa + \kappa_s + \gamma)}{4}\]
Attojoule switch

Input a few photons

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=$U(\phi)$)
- 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
The finite difference time domain method FDTD

- $E_z$-oriented dipole source
- $E_y$-oriented dipole source
- $E_x$-oriented dipole source

Number of unit cells in $\Gamma$–$K$ direction ($N_{\Gamma-K}$)

$Q$-factor

$10^3$, $10^4$, $10^5$
λ \text{res}= 536.65 \text{ nm}, \text{ Eymode}
Preliminary calculations of cavity volume and Q-factor: inverse FCC in n=3.5 material ‘silicon’.

- $V_{\text{eff}} \sim 9 \times 10^{-5} \mu m^3 = 0.19 (\lambda/2n)^3$
- $Q = 80856$
- $Q/V = 2.84 \times 10^8$
- $Q/(V)^{0.5} = 4.8 \times 10^6$

For NV centres:
- $\kappa/2\pi \sim 6 \text{ GHz}$
- $\gamma/2\pi \sim 3-10 \text{ MHz (ZPL)}$
- $g/2\pi \sim 20 \text{ GHz}$
3D Two-photon Lithography

- 200 nm
- 100 nm
- 5 µm
- 10 µm
- 2 µm
- 67 µm
- 100 µm
- 6 µm
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