Photonic devices for quantum information processing:

coupling to dots, structure design and fabrication

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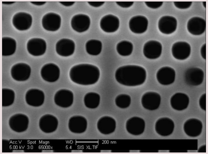
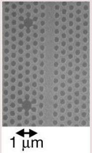
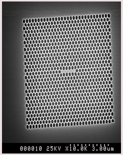
Vuckovic's group



Noda's group



Mine



Outline

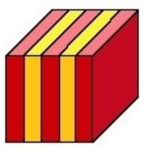
1. The ingredients
    - Photonic crystals
    - Quantum dots
2. The theoretical cake
    - Solid-state cavity QED!
    - The add-drop filter
3. Designing the recipe
    - Working principle
    - Simulations
4. Issues on the fabrication of the cake
    - Microfabrication
5. Conclusion and further cakes

Photonic crystals

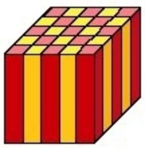
Definition

Structure with periodic modulation of dielectric constant in space

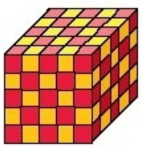
1D



2D



3D



Photonic crystals

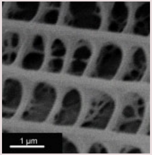
Definition

Structure with periodic modulation of dielectric constant in space

1D

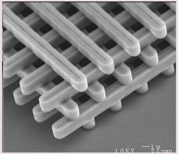
GaAs/AlAs stack

2D



Butterfly wing

3D



Si based

Photonic crystals

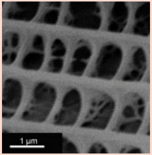
Definition

Structure with periodic modulation of dielectric constant in space

1D

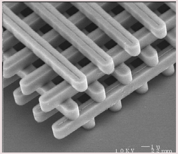
GaAs/AlAs stack

2D



Butterfly wing

3D



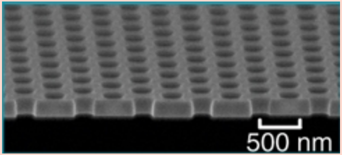
Si based

Photonic crystals

Definition

Structure with periodic modulation of dielectric constant in space

2D slabs



Free-standing membrane of air holes in semiconductor

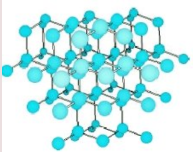
Photonic crystals

Periodic medium and unit cell

Photonic crystals

Periodic medium and unit cell

Electronic crystal

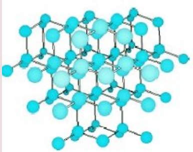


Atoms in diamond structure

Photonic crystals

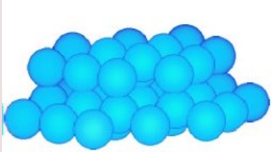
Periodic medium and unit cell

Electronic crystal



Atoms in diamond structure

Photonic crystal



Dielectric spheres in diamond lattice

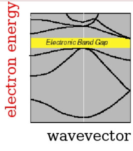
Photonic crystals

Bloch waves and bandgap formation

Photonic crystals

Bloch waves and bandgap formation

Electronic crystal



Atoms in diamond structure

Photonic crystals

Bloch waves and bandgap formation

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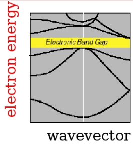
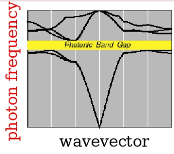


Atoms in diamond structure

Photonic crystal



Dielectric spheres in diamond lattice

Photonic crystals

Definition

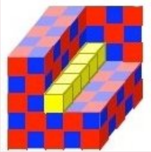
Structure with periodic modulation of dielectric constant in space

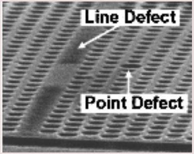
It follows that...

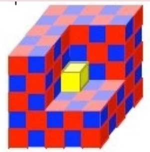
- Photonic crystals present discrete translational symmetry
- Forbidden propagation of photons within certain energy ranges, in determined crystal directions
- Light transmission properties dictated by geometry, periodicity, and dielectric constants of media composing the crystal (*and not by some atomic-scale property!*)

(Intentional) defects in photonic crystals

Local breaking of translational symmetry ("photonic doping")







Effect

Introduction of peaks in the density of states of the crystal falling within the bandgap

(Intentional) defects in photonic crystals

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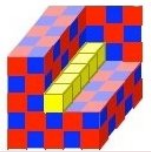
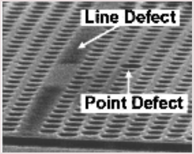
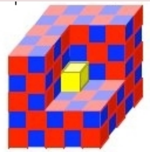




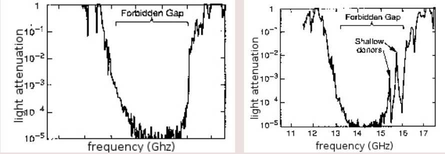


Effect

Localized/evanescent field modes with complex wave vector become (physical) solutions of Maxwell's equations, decaying exponentially from the defect

(Intentional) defects in photonic crystals

If defect = suppressed air holes ("donor defect") then

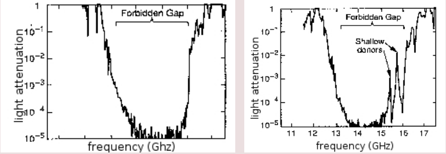


Unperturbed crystal → With defect

Tayloring defects → localization and trapping of evanescent modes

Defect cavities in photonic crystals

If defect = suppressed air holes (”donor defect”) then



Unperturbed crystal → With defect

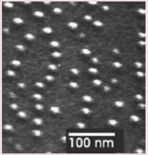
Tayloring defects → localization and trapping of evanescent modes

Quantum dots

Definition

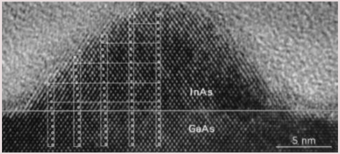
Semiconductor nanostructures confining carriers in 3D

Self-assembled InAs dots



Density $\sim 10^{10} dots/cm^2$

Nucleation by strain (lattice mismatch)



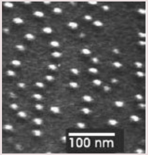
Grown by MBE on GaAs substrate

Quantum dots

Definition

Semiconductor nanostructures confining carriers in 3D

Self-assembled InAs dots



Density $\sim 10^{10} dots/cm^2$

Bandgap InAs < GaAs

$\downarrow$

carriers confined

$\downarrow$

only discrete energy levels can be occupied

Quantum dots

Definition

Semiconductor nanostructures confining carriers in 3D

It follows that...

- Carriers present a discrete spectrum: "artificial atoms"
- Photoemission range: $\sim 900 - 1100nm$ (isotropic)
- Dipole moment: $d \sim 10 - 100\times >$ atomic dipole moment $\longrightarrow$ enhanced coupling to light

Quantum dots

Definition

Semiconductor nanostructures confining carriers in 3D

Bear in mind...

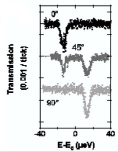
- Ideal QD $\sim$ perfecly circular disk $\longrightarrow$ only one neutral exciton line
- Real QD $\longrightarrow$ neutral exciton split in orthogonal polarisation peaks via *spin-spin electron-hole exchange interaction*

Quantum dots

Definition

Semiconductor nanostructures confining carriers in 3D

Neutral exciton split



Why put together PhC and QDs?

Solid-state cavity QED!

Model

Parameters and assumptions

- Defect acting as a cavity:

  ω_{cav}
  $\gamma_{cav} \sim 100\mu eV \longrightarrow \tau_{cav} \equiv \frac{1}{\gamma_{cav}} \sim 1ps$
  quality factor $Q \equiv \frac{\omega_{cav}}{\gamma_{cav}}$
  mode volume V
- QD as point-like emitter, placed at the antinode of a PhC defect cavity in-plane electric field mode E:

  ω_{QD}
  $\gamma_{QD} \sim 5\mu eV \longrightarrow \tau_{QD} \equiv \frac{1}{\gamma_{QD}} \sim 1ns$
  dipole moment d
- Enhanced interaction light-matter

Model

Hamiltonian

- Exciton-photon coupling parameter $2g$ (*Rabi splitting*):

$$2g = \frac{2|\langle d \cdot E \rangle|}{\hbar}$$

- Eigenfrequencies in resonance ($\omega_{QD} = \omega_{cav} \equiv \omega_{res}$):

$$\Omega_{\pm} = \omega_{res} - \frac{i}{4}(\gamma_{QD} + \gamma_{cav}) \pm \sqrt{g^2 - (\frac{\gamma_{QD} - \gamma_{cav}}{4})^2}$$

Two regimes

Weak coupling

- $$2g \ll \left|\frac{\gamma_{QD} - \gamma_{cav}}{2}\right| \quad \rightsquigarrow \quad \Omega_+ = \omega_{res} - i\frac{\gamma_{cav}}{2}$$ $$\Omega_- = \omega_{res} - i\left(\frac{\gamma_{QD}}{2} + \frac{2g^2}{\gamma_{cav}}\right)$$
- Irreversible energy transfer
- Control of the spontaneous emission rate: increase (decrease) for QDs in resonance (out of resonance) with the cavity
- $\frac{Q}{V}$

Two regimes

Strong coupling

- $$2g > \left|\frac{\gamma_{QD} - \gamma_{cav}}{2}\right|$$

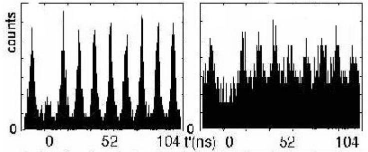
  $\longrightarrow$ spontaneous emission spectrum split by

  $$2\hbar\sqrt{g^2 - \left(\frac{\gamma_{QD}-\gamma_{cav}}{4}\right)^2}$$

  $\longrightarrow$ average linewidth $\frac{(\gamma_{QD}+\gamma_{cav})}{2}$
- Coherent energy transfer
- $\frac{Q}{\sqrt{V}}$

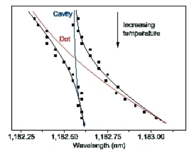
Two regimes

Weak coupling



Single photon source

Strong coupling



Anti-crossing

Applications

Generally speaking...

Linear optics Qcomp, Qrepeater, Qmemory, QDlaser...

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Linear optics Qcomp, Qrepeater, Qmemory, QDlaser...

In particular...

- Photon storage in a single exciton
- State storage in a single photon (what about state transfer?)
- Interface among different kinds of qubits

Applications

Generally speaking...

Linear optics Qcomp, Qrepeater, Qmemory, QDlaser...

In particular...

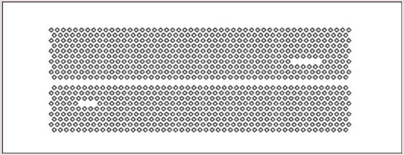
- Photon storage in a single exciton
- State storage in a single photon (what about state transfer?)
- Interface among different kinds of qubits

static qubit (QD) $\leftrightsquigarrow$ flying qubit (photon) $\leftrightsquigarrow$ static qubit (QD)

The add-drop filter

static qubit (QD) $\leftrightsquigarrow$ flying qubit (photon) $\leftrightsquigarrow$ static qubit (QD)

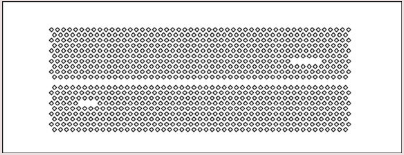
Proposed structure



Defect cavities (L3, L5) with embedded dots connected through a defect waveguide

Working principle

Proposed structure



Defect cavities (L3, L5) with embedded dots connected through a defect waveguide

Excite a QD randomly placed at the input cavity to the point it emits an in-plane photon (*centered or not around the cavity resonance!*)

↓

photon transfer via waveguide

↓

at its proximity, the output cavity traps the photon

↓

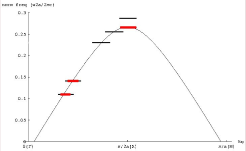
one out-of-plane photon is emitted to free space (and analysed)

Coupled mode theory (forget about the QDs for a while!)

Interaction waveguide/cavity via electromagnetic field

- Defect cavity can act as transmitter in-plane → vertical direction (*even with mismatch waveguide mode/cavity resonance!*)
- Waveguide: discrete translational symmetry + important dispersion effects (*Not regular treatment!*) ⟶ toy model

Toy model dispersion relation for (arbitrary) photonic waveguide

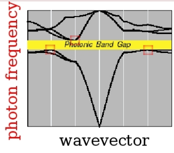


Coupled mode theory (forget about the QDs for a while!)

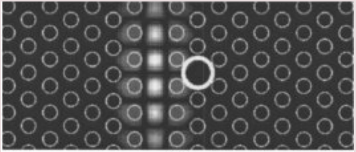
Non linear dispersion regime

- Edges of the band: group velocity $\equiv \frac{\partial \omega}{\partial \mathbf{k}} \rightarrow 0$ $\longrightarrow$ standing waves that spread into the lattice
- ω_{res} close to waveguide band edge mode $\longrightarrow$ light scattered with ω_{edge}

Band level-off at the edges



Simulated in-plane E for waveguide band edge mode



Coupled mode theory (forget about the QDs for a while!)

Non linear dispersion regime

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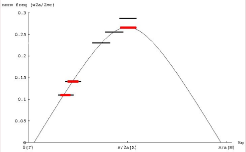
Toy model dispersion relation for (arbitrary) photonic waveguide

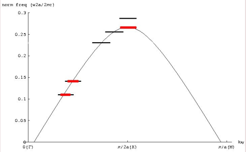


Coupled mode theory (forget about the QDs for a while!)

Linear dispersion regime

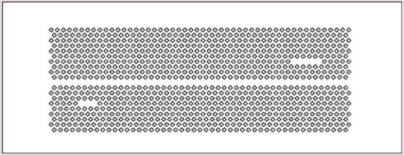
- Cavity resonance ω_{res} in the linear dispersion of the waveguide ⟶ light scattered with ω_{res} (by resonant tunneling)

Toy model dispersion relation for (arbitrary) photonic waveguide



Working principle in detail (QDs are back)

Proposed structure



Defect cavities (L3, L5) with embedded dots connected through a defect waveguide

Suppose that...

- Output cavity ω_{res} sits at non linear dispersion region of waveguide, but $\omega_{res} < \omega_{edge}$

(Suppose) QD in input cavity emits an in-plane ω_{edge} photon

$\downarrow$

photon transfer via waveguide

$\downarrow$

at its proximity, the output cavity traps the photon

$\downarrow$

one out-of-plane photon is emitted to free space (and analysed)

$\swarrow \qquad \searrow$

$\omega_{edge} \longrightarrow \nexists \qquad \omega_{res} \longrightarrow \exists$

interaction with dot

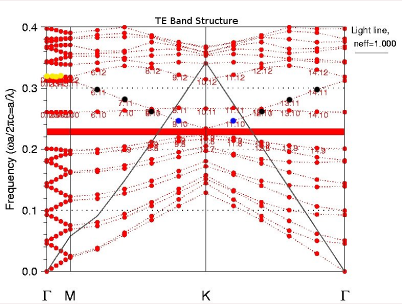
Photonic lattice and slab

Desired properties

- Study confinement of in-plane E ⟶ broad bandgap for in-plane E (TE $modes$) ⟶ hexagonal lattice with lattice constant $0.240\mu m$
- Compromise between quantities increasing with radius of air holes: bandgap × mode tendence to leak to free space ⟶ radius $0.084\mu m$
- Dots photoemission range: $\sim 900 - 1100nm$ ⟶ photonic bandgap falling within it ⟶ *(2D plane wave expansion calculated)* bandgap $[0.710, 1.012]\mu m$
- Height of slab ⟶ constrained by available sample ⟶ thickness $0.200\mu m$

Waveguide

2D plane wave expansion calculated defect waveguide band structure

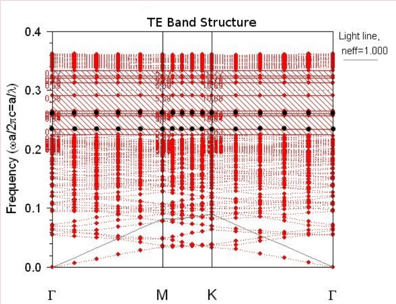


It means that...

- *Not the standard procedure for calculating waveguide supported modes!*
- Marked eigenfrequencies: guided modes
- Estimated coupling edge $[0.976, 1.026]\mu m$

(Isolated) defect cavities

2D plane wave expansion simulated band structure for crystal with L3 defect cavity

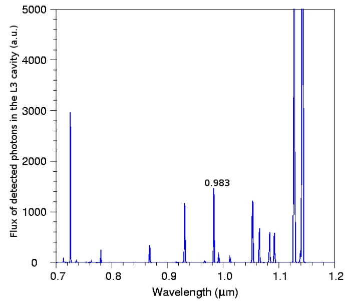


It means that...

- Simulated fundamental resonant wavelengths:
  $L3 \longrightarrow 1.026\mu m$
  $L5 \longrightarrow 1.030\mu m$
- Monomode cavity for range of order $\sim 0.060\mu m$ $\longrightarrow$ good optical selectivity of trapped modes

(Isolated) defect cavities

3D FDTD simulated resonant spectrum for crystal with L3 defect cavity

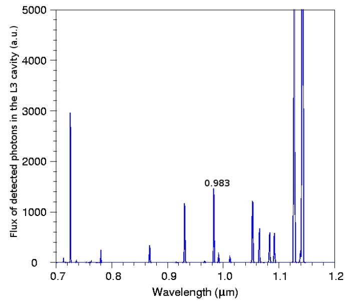


It means that...

- Spectrum computed at the center of the slab
- Simulated fundamental resonant wavelengths:
  L3 $\longrightarrow 0.983\mu m$
  L5 $\longrightarrow 1.010\mu m$
- Simulated fundamental resonant wavelengths 2D $>$ 3D

(Isolated) defect cavities

3D FDTD simulated resonant spectrum for crystal with L3 defect cavity

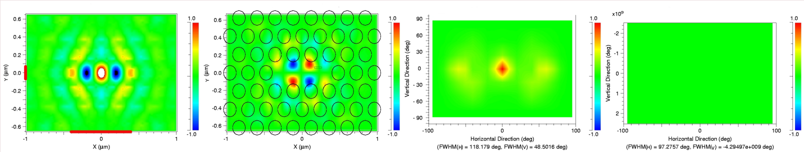


It means that...

- Quality factors for the fundamental modes:
  L3 ⟶ 820
  L5 ⟶ 410

(Isolated) Defect cavities

3D FDTD simulated fundamental mode profiles for L3 cavity



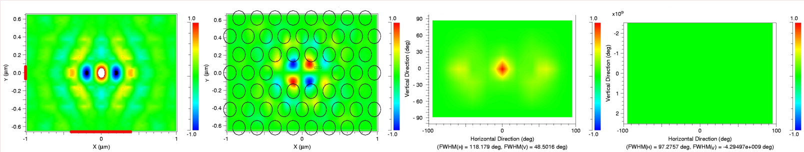
Ey near-field *Ex* near-field *Ey* far-field *Ex* far-field

It means that...

- Near-field ← *FT* → far-field
- By *FT* separately *Ex* and *Ey* ⟶ polarization and radiation angle information of scattered light

(Isolated) Defect cavities

3D FDTD simulated fundamental mode profiles for L3 cavity



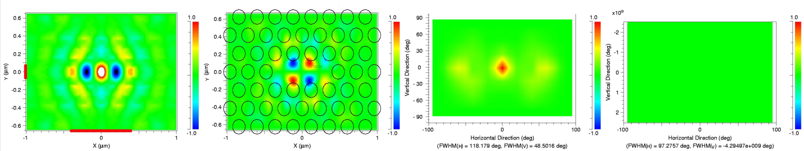
Ey near-field *Ex* near-field *Ey* far-field *Ex* far-field

It means that...

- Scattered light from the cavity is vertically emitted *and y* polarised

(Isolated) Defect cavities

3D FDTD simulated fundamental mode profiles for L3 cavity



Ey near-field *Ex* near-field *Ey* far-field *Ex* far-field

Real QD exciton has a natural linear polarisation basis ⟶ **maybe** cavity could address only the *y* polarized exciton

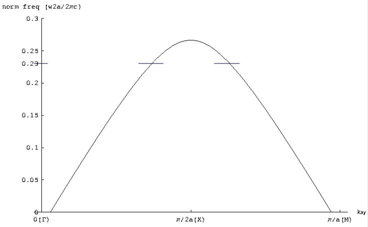
Come together

Simulations methods compared

Defect	**2D wl.** (μm)	**3D wl.** (μm)	**Discrepancy**(%)
hex. latt.	0.719-1.176	0.710-1.012	0.6-7.5
L3	1.026	0.983	2.1
L5	1.030	1.010	1.0
wg.	0.755-0.976	0.985-0.995	13.2-1.0
wg. edge	0.976-1.026	-	-

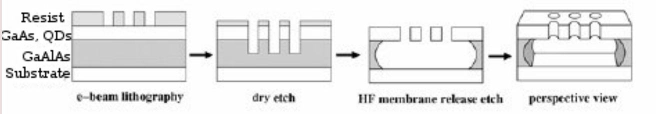
Come together

Simulated dispersion relation for modelled photonic waveguide

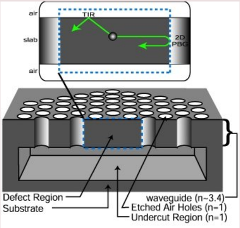


Microfabrication

Processing

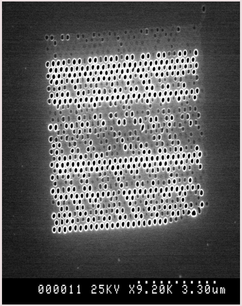


Importance of slab



Microfabrication

Results in the QDs sample

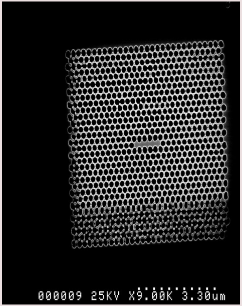


Limitations of the technique

- Random position of QDs
- Holes not uniformly etched
- Backscattering of electrons during e-beam lithography ⟶ changes in hole radia
- Worse optical confinement than if it were a free-standing membrane

Microfabrication

Results in the QDs sample



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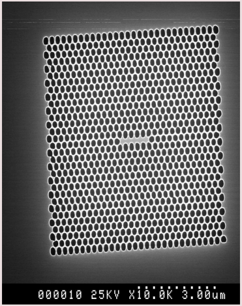

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Conclusion

In summary

- PhC structures suitable for strong *and* weak couplings to QDs
- Inexpensive and easy (!!!) technique
- Ideal platform for integration ⟶ Qnetwork, Qrepeater...
- Scalable

References

In order of appearence!

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Acknowledgements

My sincere thanks to...

- Dr. Frederic Brossard for the help with fabrication
- Dr. David Williams, director of the Hitachi Cambridge Lab, for the experienced advice
- Trinity College, for a research scholarship and a stimulating intellectual environment