Quantum dots: Physics, technology and applications

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Outline:
- Self-assembled quantum dots
- Laser applications
- Single QDs
Quantum dots

Electrons in GaAs, $T=300K$:

$\Delta E > kT \iff L < \lambda \approx \frac{h}{\sqrt{2m^*kT}} \approx 30 \text{ nm}$

QD lasers:

Single QD devices:

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Why care about QDs?

Or: The QD "dream"
Density of states and carrier distribution

\[ n(E) = g(E) \cdot f(E) \]

Density of states \hspace{2cm} Fermi distribution

Bulk: \[ g(E) \propto \sqrt{E - E_c} \]

- Low peak gain
- Temperature sensitivity
Heterostructures

Semiconductors with different gap

Heterostructure potential for electrons

Schrödinger eq.:

\[
\left( \frac{p^2}{2m} + V_{\text{crist}}(\mathbf{r}) + V_{\text{het}}(\mathbf{r}) \right) \psi(\mathbf{r}) = E\psi(\mathbf{r})
\]

\[
\psi_k(\mathbf{r}) = u_k(\mathbf{r})\chi(\mathbf{r})
\]

\( u_k \): Bloch function
\( \chi \): envelope function

\[
\left( \frac{p^2}{2m} + V_{\text{het}}(\mathbf{r}) \right) \chi(\mathbf{r}) = E\chi(\mathbf{r})
\]
2D nanostructures: Quantum Wells

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Only marginal improvement in the gain linewidth
1D nanostructures: Quantum Wires

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Density of states

\[ \rho_c(E) \propto \frac{1}{\sqrt{E - E_n}} \]

Carrier distribution

Narrower population distribution
OD nanostructures: Quantum Dots

\[ \rho_c(E) \propto \delta(E - E_n) \]

\[ \Delta E \gg kT \]

All carriers at the same energy

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Narrower gain makes better lasers

Gain calculation:
Arakawa, Sakaki 1982
Asada et al., 1986

- Lower threshold current
- Lower temperature sensitivity
- Larger modulation bandwidth

NB: Idealized picture !!!
Real QDs

Or: The shattered dream?
Nanostructure fabrication: Quantum Dots

"Straightforward" approach: Fabrication on the nanoscale

- Need high-resolution lithography
- Etching $\Rightarrow$ Nonradiative defects

"Self-organized" methods: Making Nature work for us!

- Growth on patterned substrates
- Strain-driven growth on planar substrates

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Self-assembled growth

Epitaxial growth: Interplay of surface energy and strain

"Standard" (Frank-van der Merve) 2D epitaxial growth:

Stranski-Krastanow 3D growth mode (strain-driven):

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Self-assembled quantum dots

MBE growth of InAs on GaAs:

😊 Simple growth technique, no pre-growth patterning required
😊 High crystalline quality ⇒ High radiative efficiency at RT
😊 1.3 µm operation possible

😊 Random nucleation sites ⇒ no control of island position
😊 Size dispersion ⇒ Emission energy dispersion

Atomic Force Microscopy

Transmission Electron Microscopy

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Inhomogeneous broadening

1 µm diameter:

300 nm diameter:

Macrophotoluminescence (MacroPL) at 5K:

Inh. broad.

Gain FWHM: $\Delta E_{QDs} \approx \Delta E_{QWs}$

Dot density: 300 dots/µm²
Can we do better? Controlling self-assembly

- SK growth on prepatterned substrates


Site-controlled... vs self-assembled
Homogeneous linewidth

Single-QD photoluminescence:

\[ \Gamma = \frac{2\hbar}{T_2} = \frac{2\hbar}{\tau_{life}} + \Gamma_{phon}(T) \]

- T<2 K: lifetime-limited
- 2 K<T<60 K: acoustic phonons
- T>60 K: optical phonons

Radiative dephasing Phonon scattering

(Bayer et al., PRB 2002)

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Radiative properties

MBE growth of InAs on GaAs:

**QD characteristics:**
- 1300 nm emission on GaAs
- Radiative efficiency $\approx 20\%$ at RT
- Long carrier lifetime $\approx 1\text{ns}$
- Density: $\approx 3 \times 10^{10} \text{ cm}^{-2}$

Excited states:

A. Zunger, MRS Bulletin 1998

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QD lasers (1):
The physics of a different laser
QD lasers

EPFL QD lasers:

Laser performance:
- \( J_{th} < 200 \text{ A/cm}^2 \)
- \( \eta_{ext} = 30\text{-}40\% \)
- CW up to 80 C

As-cleaved, RT:

600 \( \mu \text{m} \), HR coated 95%:

HR coatings and measurements:
O. Gauthier-Lafaye, Opto+  Andrea Fiore
A summary of laser performance

To The Best Of My Knowledge:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1.3 µm on GaAs</th>
<th>1.55 µm on InP</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;0&lt;/sub&gt;</td>
<td>&gt;200 K</td>
<td>&gt;84 K</td>
<td>Shchekin 2002, Schwertberger 2002</td>
</tr>
<tr>
<td>LEF</td>
<td>&lt;1</td>
<td>&lt;3</td>
<td>several groups, Ukhanov 2002</td>
</tr>
<tr>
<td>10 Gb/s</td>
<td>YES</td>
<td>NO</td>
<td>Hatori 2004, Kuntz 2005</td>
</tr>
</tbody>
</table>

1.3 µm on GaAs is better mastered

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The quantum side of QDs

Quantum Dots: Are they really different *(better?)* than QWs?

Fact:

Inhomog. + homog. broadening makes gain linewidth \(\approx\) QWs

... But still it is a different laser!

Confinement-related aspects:

- Discrete n. states
  - Low \(J_{tr}\)
  - Low max gain
- Excited states
  - Intraband dynam.
- Localization
  - Thermal equil.?
The role of the density of states

Transparency current:

\[ I_{tr} \propto \frac{\rho(E)}{\tau} \]

Maximum gain per pass:

\[ g_{\text{max}} = \frac{\pi e^2 x_{\text{ev}}^2 \omega}{e_0 n c} \rho(E) \]

1300 nm QDs on GaAs:

\[ (g_s = 3 \times 10^{10} \text{ cm}^{-2}, \Delta E_{\text{inh}} = 20 \text{ meV}) \]

QDs have \( \approx 10 \) times lower density of states

- Low transparency current
- Low max gain

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Record threshold current density

N quantum dots $\Rightarrow$ 2N states

Room-temperature:

$J_{th} = 33$ A/cm$^2$

$J_{tr} = 9$ A/cm$^2$

Theoretical estimate for $J_{tr}$:

$(N_{QD} = 2, g_s = 3 \times 10^{10}$ cm$^{-2}$, $\tau = 800$ ps)

$J_{tr} = N_{QD} \frac{e g_s}{\tau} = 12$ A/cm$^2$

BUT: Modal gain per QD layer $\approx 3$-4 cm$^{-1}$

Huang et al., Electron. Lett. 2000

• Low-loss cavities
• Stack many layers

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QD stacking for max gain

10 nm spacing: QDs aligned

25 nm spacing: QDs not aligned

Strain interaction between dot layers produces vertical alignment and PL broadening

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Gain problem in QD lasers

Ground state lasing only for low loss (L>1.5 mm):

\[ N_{QD}g_{th} = \alpha + \frac{1}{L} \ln \frac{1}{R} \]

High T \Rightarrow Higher optical loss \Rightarrow Wavelength switch

L= 600µm, HR/HR coated, P= 3 mW.
Device width= 3µm

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Dual-state lasing

Markus et al., APL 2003

Violates population clamping theory ???
"Slow" intraband relaxation
(Benisty et al., PRB 1991)

\[ \tau_0 \approx 10 \text{ ps in our QDs (PL rise time)} \]

Photoluminescence:

Laser:

\[ \frac{1}{\tau_0} >> \frac{1}{\tau_{\text{spont}}} \]

\[ 1 - \frac{f_{GS}}{\tau_0} \approx \frac{1}{\tau_{\text{stim}}} \]

⇒ no relax. bottleneck
⇒ ES population

Behaviour predicted by Grundmann et al., APL 2000
Modeling 2-\(\lambda\) lasing

Rate equation model:

\[
\begin{align*}
\text{WL} & \quad f_{WL} \\
\text{ES} & \quad f_{ES} \\
\text{GS} & \quad f_{GS}
\end{align*}
\]

Model

\(\tau_0 \approx 8\) ps

Exper.

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A more general view

Carrier accumulation in non-lasing states:
• Low differential gain
• Large gain compression

\[ a = \frac{dg_{GS}}{dN_{tot}} \]

\[ \Delta n_{WL} \]

capture time from WL to QD \(\Rightarrow\) \(\Delta n_{WL}\)

capture into nonlasing QDs \(\Rightarrow\) \(\Delta n_{\text{nonlas QDs}}\)

\[ \Delta n_{GS} \ll \Delta n_{tot} \Rightarrow a = \frac{dg_{GS}}{dN_{tot}} \text{ small} \]

relaxation time from ES to GS \(\Rightarrow\) \(\Delta n_{ES}\)

\[ \Delta n_{\text{nonlas QDs}} \]

• Small \( f_{\text{rel}} \) in lasers
• High \( P_{\text{sat}} \) in SOAs

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Differential gain

\[ a = \frac{dg_{GS}}{dN_{tot}} = \frac{dg_{GS}}{dN_{GS}} \frac{dN_{GS}}{dN_{QD}} \frac{dN_{QD}}{dN_{tot}} \]

Material relaxation: \( \tau_c \)

Capture: \( \tau_0 \)

Relaxation is the limit

\( \tau_c = 1 \text{ ps}, \tau_0 = 8 \text{ ps} \):

\[ \frac{dN_{QD}}{dN_{tot}} = \frac{dN_{GS}}{dN_{QD}} \]

Differ. gain (x10^{15} cm^2)

10 QD layers, 500 \( \mu \)m, HR coated

Normalised injection rate

Differ. gain (x10^{15} cm^2)

10 QD layers, 500 \( \mu \)m, HR coated

Normalised injection rate
Gain compression

\[ g = g \left( N_{\text{tot}}, N_\phi \right) \]

\[ a_p = \left. \frac{dg_{GS}}{dN_\phi} \right|_{N_{\text{tot}}} \]

**Why???

**N_\phi = 0:**

**N_\phi** large:

**Increased stimul. em. rate**  \( \rightarrow \)  **Carrier re-distribution**

\[ f_{ES} \left( 1 - f_{GS} \right) \]

\[ \tau_0 \]

Relax. rate:
Gain compression in QD lasers

From rate equations:

$$K \approx 4\pi^2\tau_p \left(1 + A\tau_0\right)$$

Relaxation time fixes $K$  

$$\Rightarrow \text{max } f_{3dB}$$

$$K = 4\pi^2\tau_p \left(1 + \frac{\Gamma a_p}{a}\right)$$

$$\gamma \approx Kf_r^2$$

$$f_{3dB\text{max}} \approx \frac{9}{K}$$
Modulation characteristics

Model

3 QD layers
2.5 Gb/s


100 ps

10 QD layers
10 Gb/s

Exp.: Kuntz, EL 2005
Quasi-thermal equilibrium?

Inhomogeneous broadening + absence of thermal equilibrium
⇒ Broad laser line = many $\approx$ independent lasers!

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Non-equilibrium and spectral-hole burning

QDs:
- Lasing line
- \( \tau_{\text{act}}>100 \text{ ps} \)
- QDs more prone to non-equilibrium distribution

QWs:
- \( \tau_{\text{SHB}}<1 \text{ ps} \)

Additional contribution to gain compression
QD lasers (2): Prospects for application?

- Low threshold current
- Small linewidth enhancement factor
- Temperature performance

Lasers

- Broad gain, large saturation power

SOAs, SLEDs
Direct laser modulation:

Problem: Spectral broadening

Laser "chirp":

\[ \Delta v = \frac{\alpha}{4\pi} \Gamma v_g \Gamma_{l} \Delta N \]

with: \( \alpha \equiv -\frac{dn/dN}{dn_i/dN} \)

linewidth-enhancement factor

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Linewidth enhancement factor in QD lasers

Ideally:
\[ \alpha = \frac{4\pi}{\lambda} \frac{dn_{\text{eff}}}{dN} \frac{d\alpha}{dN} = 0 \]

At high bias: Excited states!

Newell et al., PTL 1999

Markus et al., JSTQE 2003
Insensitivity to feedback

Coherence collapse threshold:

\[ f_{\text{crit}} \propto \gamma^2 \frac{1 + \alpha^2}{\alpha^4} \]

\( \alpha \): linewidth enh. factor
\( \gamma \): damping rate

QDs:
- \( \alpha \) small
- \( \gamma \) large (gain compression)

Potential for isolator-free modules

Reduced feedback sensitivity


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No thermal activation if $\Delta E > kT$

Holes spread among closely-spaced levels

Shcheckin et al., APL 2002
Matthews et al., APL 2002

$\Delta E_c > kT$
$\Delta E_v < kT$

Use p-doping

T-dependence fixed by electron distribution

$T_0 > 200$ K
(Shchekin EL 2002)
QDs as amplifiers

Size dispersion

Broad gain spectrum

Carrier reservoir

Large saturation power & fast recovery time

Akiyama et al, OFC 2004

P_{sat} > 19 dBm over 120 nm

Polarisation sensitivity? Preliminary evidence of polarisation control by shape engineering (Jayavel, APL 2004)

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**QD superluminescent diodes**

GS: 55 nm FWHM  
ES: 45 nm FWHM  
**GS + ES: > 100 nm**

**Chirped QD multilayers**

**Intensity (a.u.)**

- 800  
- 500  
- 300  
- 200  
- 100  
- 50

**Wavelength (nm)**

- 1000  
- 1100  
- 1200  
- 1300  
- 1400

**Intensity (a.u.)**

- 10^{-8}  
- 10^{-7}  
- 10^{-6}  
- 10^{-5}  
- 10^{-4}

**Output power (mW)**

- 0  
- 0.5  
- 1  
- 1.5

**Current (mAmp.)**

- 10^{-7}  
- 10^{-6}  
- 10^{-5}  
- 10^{-4}  
- 10^{-3}

**Chi-ped QD multilayers**

- GaAs  
- InGaAs  
- 15% In  
- 13.5% In  
- 12% In  
- 10.5% In  
- 9% In

**EPFL & EXALOS AG (Li et al, Electron. Lett. 2005)**

**8 µm x 4mm ridge**

**120 nm**
QD lasers: Real applications coming up?

QD lasers are different, in some cases better

- Low chirp
- Feedback insensitivity
- Large $T_0$
- Broad gain

→ Low-cost 10 Gb/s transmitters

→ SOAs, tunable lasers, SLDs

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Single QDs

QD laser: (as many QDs as possible)

Single-photon emitter: (only 1 QD)
Single photon emitters

Application: Quantum cryptography

BB84 quantum key distribution

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A close look at single photons

"Classical" light sources (e.g. a laser) are Poissonian:

\[ \sigma_n^2 = \langle n \rangle \]

\[
\begin{array}{c|cccccccccc}
\hline
n & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
P(n) \langle n \rangle = 10 & 0 & 0 & 0.1 & 0.2 & 0.3 & 0.25 & 0.2 & 0.15 & 0.1 & 0.1 \\
\hline
P(n) \langle n \rangle = 1 & 0 & 0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 & 0 & 0 & 0 \\
\hline
\end{array}
\]

"Nonclassical" light source:

Single quantum system:
The quest for single-$\varphi$ sources

The simplest single-$\varphi$ sources:

- Single atoms
- Single ions
- Single molecules
- ...

Wish list for single-$\varphi$ sources:

- Compact, electrically pumped
- Efficient
- Emitting at 1300-1550 nm

$\Rightarrow$ A semiconductor LED!

(Diedrich and Walther, PRL 1987)
Isolating single QDs

High areal density

Need very high spatial resolution!

Nanomesas:

Shadow-mask apertures:

CNR-IFN Roma

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How many photons?

A dot can accommodate many carriers ⇒ many photons!

\[
\begin{align*}
2E_0 + E_1 - \Delta E'_{\text{corr}} \\
2E_0 - \Delta E_{\text{corr}} \\
E_0 \\
0
\end{align*}
\]

Total energy

useful photon!

Cascade process with emission of photons at different energies
⇒ Spectral selection of the last photon

Kiraz et al., PRB 2002

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Measuring single photons

Second-order correlation function:

Hanbury Brown and Twiss experiment (1956)

Photon anticorrelation on single semiconductor QDs:
(Michler et al., Nature 2000)
Quantum key distribution uses single photons:

- Two polarization coding sets:
  - $\uparrow = 1$
  - $\rightarrow = 0$
  - $\leftarrow = 1$
  - $\uparrow = 0$

- Alice chooses a polarization set randomly:

- Bob selects an analyzer set randomly:

- Only the bits where the same polarization sets were used are kept:
Eavesdropping on single photons

To spy, Eve must intercept the photon and retransmit it:

 photon
 "wrong" analyzer
 error

A single photon cannot be split!

By monitoring the error rate Alice and Bob can check the channel security!
Q: Do I really need a single-photon source for QKD?

**Answer: NO!**

Present QKD systems use attenuated lasers

\[ <n> \approx 0.1 \implies P(2) \approx 1\% \]

Few 2-photon pulses

With "privacy amplification" \(\Rightarrow\) Totally secure key

**PRICE TO PAY:** \[ P(1) \approx 10\% \]

Most pulses empty!

To beat lasers, a single-\(\phi\) source must be **efficient**!

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The problem of light extraction:

Total internal reflection

\[ n(\text{GaAs}) \approx 3.5 \]

\[ \eta_{\text{extr}} = \frac{\Omega}{4\pi} \approx 2\% \]

Need to change carrier-photon interaction so that light is generated only in useful directions
Electron-photon interaction described by perturbation theory:

\[ H' = -p \cdot \vec{E}_0 e^{i \omega t} \]

Coupling to a density of optical modes (or a lossy mode):

Fermi golden rule:

\[ W_{if} \propto |r_{12}|^2 \frac{g(E_2 - E_1)}{V} \]

\( g(E) \): Opt. density of states per unit energy

\( V \): Mode volume
Microcavities & QDs

\[ W_{if} \propto |r_{12}|^2 \frac{g(E_2 - E_1)}{V} \]

**free space:**

\[ g_{FS}(E) = \frac{8\pi E^2}{h^3 c^3 V} \]

**cavity:**

\[ g_{\text{cav}}^{\text{max}} = \frac{1}{\Delta E_{\text{cav}}} \]

**Sp. em. rate enhancement:** (Purcell, 1946)

\[ F_P = \frac{W_{\text{cav}}}{W_{FS}} \propto \frac{1}{\Delta E_{\text{cav}} V} \cdot \frac{1}{E^2} \propto Q \frac{\lambda^3}{V} \]

\[ F_P >> 1 \quad \Rightarrow \quad \eta \approx 100\% \]

(all photons emitted in cavity mode)
Micropillars: (Gérard et al., PRL 1998)

Decreased PL lifetime:

Factor $x5$ increase in sp. em. rate under optical pumping

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Promising candidates for high-Q microcavities

Silica toroid: $Q \approx 10^8$ !
(Armani et al., Nature 2003)

Photonic crystal $\mu$-cavity
A single QD in a 3D μ-cavity

Micropillars with single QDs:

Purcell effect:

Single-ϕ generation:

Pelton et al., PRL 2002
Vuckovic et al., APL 2003

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Quantum cryptography needs:

• **1.3 - 1.55 \( \mu m \)** emission for fibers (problem with detectors)

• **Room temperature** operation (very difficult)

• **Electrical injection** (demonstrated only with very low efficiency: *Yuan et al., Science 2002*)
Single QDs at telecom wavelengths

Very low growth rate:
Low density + long-λ

Preliminary anticorrelation experiments at Fujitsu, Toshiba Europe, EPFL
Alloing, APL 2005
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Temperature dependence

Single QD emission above 77 K:

- Population of charged exciton states at high T
- Homogeneous broadening of lines due to phonon scattering
- Single lines can be isolated up to T>77K

Towards LN$_2$-cooled single-photon sources at 1300 nm

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Fabrication of nano-LEDs

Etching:
- Defects ⇒ NR recombination
- Needs high-res. lithography

Oxidation:
- Does not create defects
- Smaller dimensions (<100 nm with optical lithography)

Fiore et al., APL 2002
Single QDs: Perspectives
• Entangled photon generation:

Two electrons ⇒ two photons (orthogonally polarized and entangled)

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A |1\rangle_B \pm |1\rangle_A |0\rangle_B) \]

• Single-photonics (towards quantum computing?):

Identical single photons "stick together"

(Santori et al., Nature 2002)
Quantum interference of two photons

Lossless symmetric beamsplitter: Input-output relations

Classical:
\[
\begin{align*}
E_3 &= \frac{1}{\sqrt{2}}(E_1 + E_2) \\
E_4 &= \frac{1}{\sqrt{2}}(E_1 - E_2)
\end{align*}
\]

Quantum:
\[
\begin{align*}
a_3^\dagger &= \frac{1}{\sqrt{2}}(a_1^\dagger + a_2^\dagger) \\
a_4^\dagger &= \frac{1}{\sqrt{2}}(a_1^\dagger - a_2^\dagger)
\end{align*}
\]

Both photons from the same port (entangled state)
2-photon interference: Experiment

"Mandel's dip":

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 10 July 1987)

A non-classical interference effect

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Asymmetric beamsplitter (R=33%, T=67%):

\[
\begin{align*}
\begin{cases}
a_3^\dagger &= \sqrt{\frac{2}{3}} a_1^\dagger + \frac{1}{\sqrt{3}} a_2^\dagger \\
a_4^\dagger &= \frac{1}{\sqrt{3}} a_1^\dagger - \sqrt{\frac{2}{3}} a_2^\dagger
\end{cases}
\end{align*}
\]

\[
|1_1 1_2\rangle = a_1^\dagger a_2^\dagger |00\rangle = \frac{\sqrt{2}}{3} \left( |2_3 0_4\rangle - |0_3 2_4\rangle \right) - \frac{1}{3} |1_3 1_4\rangle
\]

Sign shift induced by the photon collision
Photonic quantum bits:

O'Brien et al., Nature 2003:

\[ |0\rangle = \text{photon in upper branch} \]
\[ |1\rangle = \text{photon in lower branch} \]

Balanced interferometer:
If \( C = 0 \):
\[ T_{in} = 0 \rightarrow T_{out} = 0, \ T_{in} = 1 \rightarrow T_{out} = 1 \]

If \( C = 1 \):
Phase shift at 1/3 beamsplitter
\[ T_{in} = 0 \rightarrow T_{out} = 1, \ T_{in} = 1 \rightarrow T_{out} = 0 \]

NB: Works with only 1/9 probability!
"Probabilistic" quantum gates are possible using single photons, beamsplitters and phase shifters.

The probability of success can be increased arbitrarily by using teleportation and entanglement.

"Efficient" quantum computation (Knill et al., Nature 2001)

Linear optics quantum computation needs "perfect" single-photon sources and detectors (plus a few hundred optical elements….)

In the meantime, interesting quantum optics experiments:
Conclusion

QDs: A different light source

Today:
- QD lasers for telecom
- QD broad gain SOAs and SLEDs

Tomorrow:
- "Quantum" applications
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