Quantum Photonic Integrated Circuits

IHFG Hauptseminar: Nanooptik und Nanophotonik

Supervisor: Prof. Dr. Peter Michler

14.07.2016
Motivation and Contents

Photon Generation
- Quantum Dots
- Parametric Down-Conversion

Photon Manipulation
- Hong-Ou-Mandel effect
- Directional Coupler
- On-chip SFWM
- QDs in Waveguides
- Mach-Zehnder Interferometer
- Universal Linear Optical Processor

Photon Detection
- On-chip SNSPD

Future Directions and Summary
• Photons as qbits
  - low decoherence
  - high speed and lossless transmission
  - compatibility with classical photonic technology
  - easily encodeable degrees of freedom

• Degrees of freedom
  - polarization
  - path
  - time
  - orbital angular momentum

Any drawbacks?
  - Small mutual interaction
  - only probabilistic gates
• III-V Semiconductor

• Silica-on-Silicon

• Aluminum Nitride

• Polymer Integration Platforms

• Lithium Niobate
Basics and Materials – GaAs

- Direct band-gap ➔ On-chip single-photon sources
- Low loss waveguides
- High refractive index ➔ Compact devices
- Large electro-optical effect ➔ Fast routing and photon manipulation
- In-waveguide SPDC ➔ Entangled photon pairs
- High fabrication cost
Basics and Materials – Silica-on-Silicon

- Indirect band-gap \(\Rightarrow\) External light sources
- Good fiber coupling \(\Rightarrow\) Low loss
- No electro-optical effect \(\Rightarrow\) No fast modulation
- Slow thermo-optical effect \(\Rightarrow\) Refractive index modulation
- Cheap fabrication
- Compatible with Si-based microelectronics

http://www.roboternetz.de (13.07.2016)
Basics and Materials – Aluminium Nitride

- Strong second order nonlinearity
- Integrated low loss
- High speed electro-optical phase modulation
- High refractive index contrast to SiO$_2$
- No on-chip photon generation
• Only for Glass
• Fs pulse tightly focused in a glass
• Multiphoton absorption and avalanche ionization
• Ionization induces permanent and localized refractive index increase in transparent materials
Direct Laser Writing

- Circular symmetric transverse profile
- Fast device fabrication
- 3D spatial capabilities
- Low birefringence

F. Sciarrino *Quantum walk with integrated photonics* Physics Department of Sapienza University of Rome PPT (14.11.2012)
• Thermo-optical effect: \( n(\Delta T) = n_0 + \alpha \cdot \Delta T \)
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Quantum Computer

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- Basics and Materials

- Future Directions and Summary
Quantum Dots

Energy conservation $\omega_{775\text{nm}} = \omega_{1550\text{nm}} + \omega_{1550\text{nm}}$

Momentum conservation $p_{775\text{nm}} = p_{1550\text{nm}} + p_{1550\text{nm}}$

Refractive index matching $n_{\text{eff}} = pxc/\omega_x r$
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Photon Manipulation

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Future Directions and Summary
Photon Manipulation

- Pure classical states $|0\rangle$ and $|1\rangle$

- Superposition $|\psi\rangle = \cos(\theta) |0\rangle + e^{i\varphi} \sin(\theta) |1\rangle$

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Future Directions and Summary
Hong-Ou-Mandel effect

\[ |11\rangle = \frac{|20\rangle - |02\rangle}{\sqrt{2}} \]

Hong-Ou-Mandel effect URL: wikiwand.com/en/Hong–Ou–Mandel_effect (16.06.2015)
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Basics and Materials

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Universität Stuttgart
• Superposition $|\psi\rangle = \alpha |10\rangle + \beta |01\rangle$ with detection probability $|\alpha|^2$ and $|\beta|^2$

• Mathematically unitary single-qubit operation

• Coupling length and gap distance $\Rightarrow \varepsilon$

• Quantum mechanical annihilation and creation operator $\hat{a}_i$ and $\hat{a}_i^\dagger$ with port $i$
• One photon input in $1 \ |10\rangle = \hat{a}_{1}^\dagger \ |00\rangle$

\[
|10\rangle \xrightarrow{\text{DC}} (\sqrt{1 - \varepsilon} \hat{a}_3^\dagger + i \sqrt{\varepsilon} \hat{a}_4^\dagger) \ |00\rangle = \sqrt{1 - \varepsilon} \ |10\rangle + i \sqrt{\varepsilon} \ |01\rangle
\]

• Output state dependent on $\varepsilon$

• Hadamard-like operation for $\varepsilon \approx 0.5$

\[
(|10\rangle + i \ |01\rangle) / \sqrt{2}
\]
Directional Coupler

- Two photon input in 1 and 2 \( |11\rangle = \hat{a}_1^+ \hat{a}_2^+ |00\rangle \)

\[
|11\rangle \xrightarrow{\text{DC}} (\sqrt{1 - \epsilon} \hat{a}_3^+ + i \sqrt{\epsilon} \hat{a}_4^+) (i \sqrt{\epsilon} \hat{a}_3^+ + \sqrt{1 - \epsilon} \hat{a}_4^+) |00\rangle
= [i \sqrt{\epsilon (1 - \epsilon)} (\hat{a}_3^+ \hat{a}_3^+ + \hat{a}_4^+ \hat{a}_4^+) + (1 - 2\epsilon) \hat{a}_3^+ \hat{a}_4^+] |00\rangle
= i \sqrt{2\epsilon (1 - \epsilon)} ('00' + '02') + (1 - 2\epsilon) |11\rangle
\]

- Output state dependent on \( \epsilon \)

- Coherently bunched photons for \( \epsilon \approx 0.5 \)
- GaAs directional coupler

- 2.5 µm gap and 140 µm length $\implies \varepsilon \approx 0.5$

Directional Coupler

- Visibility \( V = \frac{(N_{\text{max}} - N_{\text{min}})}{N_{\text{max}}} = 94.9\% \)

- HOM-dip shape
  - FFT single-photon wave packet

- 440\(\mu\)m shoulder-to-shoulder width
  - 0.73ps coherence time
  - 64.1\(\mu\)m coherence length

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• AR coating on facets important

• Large refractive index difference at facets ➔ strong Fresnel reflections

• Forth-and-back reflections ➔ reflection probability $R$ ➔ transmission probability $T$

• Fresnel equation $R = \left( \frac{n_{GaAs} - n_{air}}{n_{GaAs} + n_{air}} \right)^2$ with $1 = R + T$ results in $R = 30\%$ and $T = 70\%$

• Extra coincidences for quantum interference
Directional Coupler

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Future Directions and Summary

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On-chip Four-Wave Mixing

J.W. Silverstone et al. On-chip quantum interference between silicon photon-pair sources
Nature Photonics 8, 2014
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QDs in Waveguides


Mario Schwartz, Ulrich Rengstl, et al.
Generation, guiding and splitting of triggered single photons from a resonantly excited quantum dot in a photonic circuit

Opt. Express 24 (3) (8.2.2016)
• Single-photon operation under pulsed excitation
• Cross-correlation measurement $g^{(2)}(0)$ of 0.18
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Future Directions and Summary

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Mach-Zehnder Interferometer (MZI)

- 2 directional coupler (DC)
- Phase shifter for superposition

Phase shifter induces $e^{-i\theta}$ shift

Electro-optical Pockels effect $\Delta n = n_0^3 \cdot r_{\text{eff}} \cdot E$

Noncentrosymmetric media

Phase difference $\Delta \varphi = 2\pi \cdot v \cdot \Delta T(\Delta n)$
Mach-Zehnder Interferometer

- Unitary operation
  \[ U_{\text{unitary}} = \begin{pmatrix} \sqrt{1-\varepsilon} & i\sqrt{\varepsilon} \\ i\sqrt{\varepsilon} & \sqrt{1-\varepsilon} \end{pmatrix} \]

- One photon input in 1
  \[ |10\rangle = \hat{a}_1^\dagger |00\rangle \]

\[ \begin{align*}
|10\rangle & \xrightarrow{\text{DC}_1} (\sqrt{1-\varepsilon} \hat{a}_3^\dagger + i\sqrt{\varepsilon} \hat{a}_4^\dagger) |00\rangle \\
& \xrightarrow{\text{Phaseshift}} (\sqrt{1-\varepsilon} \hat{a}_3^\dagger + i e^{-i\theta} \sqrt{\varepsilon} \hat{a}_4^\dagger) |00\rangle \\
& \xrightarrow{\text{DC}_2} [\sqrt{1-\varepsilon} (\sqrt{1-\varepsilon} \hat{a}_5^\dagger + i\sqrt{\varepsilon} \hat{a}_6^\dagger) + i e^{-i\theta} \sqrt{\varepsilon} (i\sqrt{\varepsilon}) \hat{a}_5^\dagger + \sqrt{1-\varepsilon} \hat{a}_6^\dagger] |00\rangle \\
& = [(1-2\varepsilon)\cos(\theta/2) + isin(\theta/2)] |10\rangle + i2\sqrt{\varepsilon(1-\varepsilon)} \cos(\theta/2) |01\rangle
\]
• Single photon detector counts $\sin^2(\theta/2) + \cos^2(\theta/2)(1 - 2\varepsilon)$ and $4\varepsilon(1 - \varepsilon) \cos^2(\theta/2)$

• Detector output for $\varepsilon \approx 0.5$: $\sin^2(\theta/2)$ and $\cos^2(\theta/2)$

• GaAs Mach-Zehnder Interferometer
  - gap distance 3μm
  - coupling length 255μm

Mach-Zehnder Interferometer

Unitary operation

$$U_{\text{unitary}} = \begin{pmatrix}
\sqrt{1-\varepsilon} & i\sqrt{\varepsilon} \\
i\sqrt{\varepsilon} & \sqrt{1-\varepsilon}
\end{pmatrix}$$

Two photon input in 1 and 2

$$|11\rangle = \hat{a}_1^+ \hat{a}_2^+ |00\rangle$$

1. **DC1:**

$$|11\rangle \xrightarrow{\text{DC}_1} [i\sqrt{\varepsilon(1-\varepsilon)} (\hat{a}_3^+ \hat{a}_3^+ + \hat{a}_4^+ \hat{a}_4^+) + (1 - 2\varepsilon) (\hat{a}_3^+ \hat{a}_4^+)] |00\rangle$$

2. **Phasenheit:**

$$|11\rangle \xrightarrow{\text{Phasenheit}} [i\sqrt{\varepsilon(1-\varepsilon)} (\hat{a}_3^+ \hat{a}_3^+ + e^{-i2\theta} \hat{a}_4^+ \hat{a}_4^+) + (1 - 2\varepsilon)e^{-i\theta} \hat{a}_3^+ \hat{a}_4^+ |00\rangle$$

3. **DC2:**

$$i\sqrt{2\varepsilon(1-\varepsilon)} [-\varepsilon e^{-i2\theta} + (1 - 2\varepsilon) e^{-i\theta} + (1 - \varepsilon)] |20\rangle +

i\sqrt{2\varepsilon(1-\varepsilon)} ((1 - \varepsilon)e^{-i2\theta} + (1 - 2\varepsilon)e^{-i\theta} - \varepsilon] |02\rangle +

[-2\varepsilon(1 - \varepsilon)e^{-i2\theta} + (1 - 2\varepsilon)^2 e^{-i\theta} - 2\varepsilon(1 - \varepsilon)] |11\rangle$$
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Basics and Materials

Universal Linear Optical Processor
Universal Linear Optical Processor

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Future Directions and Summary

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Future Directions

Challenges

- Improving functionality
- Higher density
- New operation implementation

2D

3D
Thank You

For Your Attention...