Photonic quantum information processing: a concise review

Sergei Slussarenko and Geoff J. Pryde

1 Introduction

1A - Optical Quantum Computing

Photon advantages:

- Clean and decoherence free → High fidelity
- Required for communication-based QI tasks

Photon disadvantages:

- Don’t easily interact → Makes deterministic 2-qubit gates challenging
- Imperfections in generation and detection → Photon loss
- May need quantum memory

1B - Basics

Qubit encoding

Dual rail encoding: encoding QI in the occupation of a photon in two modes of a degree of freedom. Possible degrees of freedom are

- Orthogonal polarisations

- Transverse spatial modes
- Frequency modes

Two Qubit Gates

Requires applying a π phase shift rotation on one of the qubits, depending on the state of the other qubit. This is a non-linear interaction, non-linear photon interactions are extremely weak. Therefore, it is common to mimic the interaction with a probabilistic postselection approach.

The KLM scheme is a scalable photonic scheme for QC, for an introduction see Myers and Laflamme.

2 - Photon Technology

2A - Detecting a Photon

An ideal photon detector:

- Has no false positive detections ("dark counts")
- Can determine exactly how many photons are detected in a certain spatio-temporal mode

A real photon detector is characterised by:

Metric	Symbol	Description
Detection efficiency	η_{d}	Defines maximum detection rate
Reset time	τ_{R}	
Detection time jitter	τ_{j}	
Dark count rate	C_{d}	
Photon number resolving capability	PNR	

Physical Detectors

Si Avalanche Photodiode (Si APD)

- Typically fast ($\tau_{\mathrm{R}} \leq 100\ \mathrm{ns}$)
- Low noise ($C_{\mathrm{d}} \sim 100$ counts per second)
- Low efficiency ($\eta_{\mathrm{d}} \approx 65\%$)

- Limits number of photons that can be used experimentally since detecting 10 photons with 10 detectors is 2% and this gets exponentially worse

- No PNR capabilities
- Limited maximum efficiency wavelength band (does not cover the telecom band of 1310-1550 nm)

Superconducting Nanowire Single-Photon Detectors (SNSPD

- Works by passing a current through a superconducting nanowire close to the critical current, the absorption energy of a single photon can transition the device to normal resistivity, resulting a in a voltage spike
  - Requires cryogenic temperatures (0.8-3K)
- Fast resent time ($\tau_\mathrm{R} \approx 40\ \mathrm{ns}$)
- Detection efficiencies of up to $\eta_\mathrm{d} \geq 0.95$ [ref]
- Lacks PNR capability, although one potential scheme exists [ref]
- Thermal noise can be reduced via spectral filtering

Transition Edge Sensors

- Absorption near the transition edge changes the device resistance monotonically with photon number
- Shown to be able to discriminate as many as 20 photons in the same spatio-temporal mode [ref]
- Seen to reach $\eta_\mathrm{d} \approx 0.98$ in the telecom range
- Long reset times τ_R of the order of μs (best seen at $460\mathrm{ns}$)
- Long jitter times of over $50\mathrm{ns}$ (best seen at $2.3\mathrm{ns}$)
- PQC requires clock cycles of $\leq 10\ \mathrm{ns}$

2B - Generating a Photon

PQC will requires the simultaneous generation of large numbers of single photon states ($\mathrm{N} \approx 10 - 10^{11}$). The photons must be:

- Efficiently collected, without loss due to absorption, scattering, diffraction or mode mismatching
- In a pure quantum state and be indistinguishable

Possible physical realisations are trapped ions and atoms, colour centres in diamond, semiconductors and quantum dots.

Spontaneous Parametric Down Conversion (SPDC)

Pump photon from a laser has a small probability of being converted into a pair of daughter photons known as signal and idler photons. This process is not deterministic, however the photons can be heralded.

Simple SPDC

Typical SPDC in a simple, phase-matched, bulk-crystal source is not suitable as the transverse spatial profile is far from a Gaussian mode and therefore does not couple well into a single mode fibre → losses. In addition at 800nm (convenient for Si APDs and pump lasers) material losses are high and the detection efficiency is limited. This results in typical heralding efficiencies of $\leq 10-15\%$, however up to 30% has been achieved [ref].

Quasi-Phase Matching (QPM) SPDC

- Possible using periodically poled non-linear crystals
- Increases range of possible phase-matching wavelengths, emission geometries and enables beam-like, collinear downconversion in the telecom range
- Results in photon pairs emitted into an almost single, identical and Gaussian spatial mode → mode-matching and fibre loss is very low → High heralding efficiencies

Group Velocity Matching (GVM)

- Adjusting the group velocities of the pump, signal and idler photons, the pump bandwidth and the APDC crystal length → the joint spectrum of the daughter photons can be controlled
    - Allows emission of signal photon in a specific spectral mode and the idler photon in a different spectral mode with high fidelity
-