All-optical Switching for Photonic Quantum Networks

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Classical vs. Quantum Communication

Alice

Classical bit: 0 or 1

Quantum bit: $|\psi\rangle = \alpha |0\rangle + \beta |1\rangle$

Bob

Error-free communication below channel capacity

$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle$

Conflict with Quantum Mechanics

- No-cloning theorem
  - It is impossible to duplicate an unknown quantum state

- Heisenberg uncertainty principle
  - It is impossible to know a quantum state
Qubit Teleportation using Singlet States*

Transmitter T and Receiver R share entangled qubits

\[ |\psi\rangle_{TR} = \left( |0\rangle_T |1\rangle_R - |1\rangle_T |0\rangle_R \right) / \sqrt{2} \]

- \[ |\psi\rangle_{in} = \alpha |0\rangle_{in} + \beta |1\rangle_{in} \] Transmitter accepts input qubit and makes measurements on the joint state of the input qubit and Transmitter’s part of the entangled qubit.

- Measurement results (two classical bits) sent to Receiver.

- Simple transformation at Receiver yields \[ |\psi\rangle_R = \alpha |0\rangle_R + \beta |1\rangle_R \]

• Classical EM-field supports noiseless oscillation
  – Phasor representation of single mode: \( a e^{-i \omega t} \)
  – Quadrature representation of the phasor: \( a = a_1 + ia_2 \)
• Quantum EM-field obeys uncertainty principle
  – Operator representation of single mode: \( \hat{a} e^{-i \omega t} \)
  – Quadrature decomposition of annihilation operator: \( \hat{a} = \hat{a}_1 + i\hat{a}_2 \)
  – Quadrature uncertainty principle: \( \langle \Delta \hat{a}_1^2 \rangle \langle \Delta \hat{a}_2^2 \rangle \geq 1/16 \),
• Coherent state: \( \langle \Delta \hat{a}_1^2 \rangle = \langle \Delta \hat{a}_2^2 \rangle = 1/4 \)
• OPA output modes are quadrature entangled:
  \( \langle (\Delta \hat{a}_{s_1} - \Delta \hat{a}_{i_1})^2 \rangle = s/4 \) and \( \langle (\Delta \hat{a}_{s_2} + \Delta \hat{a}_{i_2})^2 \rangle = s/4 \), where \( s < 1 \)

CV = continuous variable; EM = electromagnetic; OPA = optical parametric amplifier
Teleportation via Field Quadratures*

**Transmitter Station**

- Optical Parametric Amplifier
- Homodyne Detector $\theta = 0$
- Signal output
- 50/50 Beam Splitter
- Homodyne Detector $\theta = \pi/2$
- Classical data: Send to receiver
- Auxiliary output
- Light beam: Send to receiver
- Coherent-State Source
- Classical Data: From Transmitter
- Auxiliary Output: From Transmitter
- Teleported State

**Receiver Station**

- Classical data: Send to receiver
- Homodyne Detector $\theta = \pi/2$
- Classical data: Send to receiver
- 50/50 Beam Splitter
- Homodyne Detector $\theta = 0$
- Signal output
- Auxiliary output
- Light beam: Send to receiver
- Coherent-State Source
- Classical Data: From Transmitter
- Auxiliary Output: From Transmitter
- Teleported State

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Quantum Communication (QC) and Quantum Information Processing (QIP)

**QC:** Sending quantum information between two or more quantum nodes

**QIP:** Manipulation of qubits with quantum logic gates

*Ultimate goal — a quantum computer*
Desirable Features of an Entanglement Source

• Should produce and send copious amounts of pairs at high rate
• Entanglement should not degrade as the pairs are distributed

Entangled Photon-Pair Source
Progress Towards Practical Quantum Communications

- Near infrared systems based on $\chi^{(2)}$ crystals, bulk as well as waveguide

- Telecom band systems based on optical fibers & more recently, integrated silicon-photonic type platforms

- Atomic ensembles for long-distance QC and for narrowband photons to match with atomic quantum memories
Parametric Fluorescence in Optical Fiber

- Signal and idler photons are created in pairs
- They exhibit entanglement properties

At the Quantum Level:

- Signal and idler photons are created in pairs
- They exhibit entanglement properties

Strong parametric fluorescence is easily observed at moderate pump power

M. Fiorentino et al., IEEE PTL 14, 983 (2002)
X. Li et al., PRL 94, 053601 (2005)
Fiber-Based Source of Polarization-Entangled Photons

\[ \lambda_p = 1538.7 \text{ nm} \]
\[ \tau_p = 5 \text{ ps} \]

300 m DSF on a spool

Signal at 1533.9 nm
Idler at 1543.5 nm

Filter >100 dB
Polarization Analyzers

Fiber-Based Source of Polarization-Entangled Photons

90/10

HWP
QWP
PBS1
FP
FP
FP

\[ \omega_s, \omega_p, \omega_I \]
High-Purity Polarization Entanglement

Practical Source Available from NuCrypt LLC, Evanston, IL

User A

User C

User B

User D

TPI at 4 different bases, $-196^\circ$C

OFC-2009 Postdeadline Paper PDPA3
Multi-Channel Fiber-Based Source of Polarization Entangled Photons with Integrated Alignment Signal

Contact: kanterg@nucrypt.net

NuCrypt
Securing Optical Communication Networks
Source Summary and Scaling to 10 GHz

- **Pump Pulse Characteristics**
  - Rep rate = 50 MHz
  - Typical pulse width 35 ps (about 0.15 nm transform limited bandwidth)
  - Avg. photon # / pulse: $10^7$–$10^8$ for pair production prob. 1–5% in ~100 m DSF
  - Typical average power ~ 2 mW
- At 50 MHz rate, the source produces >100,000 entangled pairs / second
- Scales to >20 million entangled-pairs/s at 10 GHz pulse rate
- Required average pump power ~ 400 mW
  - Easily achievable with mode-locked lasers with amplification
- However, single-photon detection is still a bottleneck for developing quantum communication applications in the telecom band
  - InGaAs-based APDs can be gated up to 1–2 GHz (long dead time)
  - Faster superconducting detectors on the horizon, but still not available
- Optical demultiplexing is a potential near-term solution
All-Optical Switches for Quantum Applications

- High switching contrast
- Low pump power threshold
- Low signal loss
- Quantum state preservation

Pump
Classical or Quantum (Fredkin gate)
Outline

• Need for All-optical Quantum Switches
  – Mux / Demux high-speed photon-pair sources
  – Heralded single-photon generation

• Ultrafast Switching of Photonic Entanglement
  – Switch characterization
  – Comparison with theory (no fitting parameter)
  – Development of a full cross-bar switch

• Quantum Switch Applications
  – Ultrafast MUX / DEMUX of quantum data channels
  – Measurement of time-bin entangled qudits

• Conclusions and Future Outlook
Quantum Switch Design based on Cross-Phase Modulation (XPM) in Fiber

Unitary evolution in absence of Raman

\[ b(t) = a(t) \exp\left(i \gamma L_{\text{eff}} \int P(t') dt' \right) \]

Two-Color Pump Pulses in the C-band for Polarization Independent Switching
Towards Applications in Embedded Fiber Telecom Infrastructure

Create entangled photon-pairs in the 1310 nm band

From C-band Classical Com Channels

Ultrafast Entanglement Generation

Pulses carved from a CW or ML laser

\[ \lambda_p = 1305 \text{ nm} \]

\[ \tau_p = 100 \text{ ps (30 ps with MLL)} \]

- 1.5 nm detuning from pump
  - Reduced spontaneous Raman scattering
- Mode-locked (ML) laser allows 10 GHz Operation

Hall, Altepeter, & PK, OpEx 17, 14558 (2009)
Source Stability Testing

Fidelity to Initial State

Pump laser turned off

Pump laser and Detectors turned off

Time (hours)

Hall, Altepeter, & PK, NJP 13, 105004 (2011)
Switch Location for Quantum Testing

Diagram showing the switch location for quantum testing with various components and labels such as DGF, Circ, PDD, etc. The diagram includes labels for signal and idler paths, pump pulse carving, and quantum states like |HH⟩ and |VV⟩. The diagram also shows the connection to 500 m SMF-28 fiber and detectors D1, D2, D3, and D4.
Ultrafast Switching of Photonic Entanglement

Design:

- Pump Input
- WDM
- Circ
- 50:50
- Switch Input
- Switch Output 1
- Switch Output 2
- Pump Output

Entangled State Fidelity:
- Passively Switched
  - F = 99.6%
- Actively Switched
  - F = 99.4%

Loss:
- Switch 0.9 dB
- Circulator 0.4 dB

Switching Contrast: 200-to-1

Switching Window: 850 ps (500 m); 170 ps (100 m)

Hall, Altepeter, & PK, NJP 13, 105004 (2011)
Full Cross-Bar Operation: Coincidence Switching Windows


20-m Common Fiber
• ~40-ps Window
Quantum Theory of Kerr Switching

**Starting Point:** A general Heisenberg equation for traveling waves

\[
\frac{\partial \hat{A}_j(z, t)}{\partial z} = i \sum_k \left[ \int_{-\infty}^{t} R_{jk}^{(1)}(t - t') \hat{A}_k(z, t') dt' + \sqrt{\hbar \omega_0} \hat{m}_{jk}(z, t) \hat{A}_k(z, t) \right] + i \sum_{klm} \int_{-\infty}^{t} R_{jklm}^{(3)}(t - t') \hat{A}_k^+(z, t') \hat{A}_l(z, t') \hat{A}_m(z, t) dt'.
\]

- Chromatic dispersion, propagation loss, …
- Spontaneous Raman scattering

Result: Input/output transformation with the inclusion of quantum-noise

\[
\begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} = e^{i\varphi(t)} e^{-\ell_s} \begin{pmatrix}
\cos \theta(t) & i \sin \theta(t) \\
i \sin \theta(t) & \cos \theta(t)
\end{pmatrix} \begin{pmatrix}
\hat{a}_1 \\
\hat{a}_2
\end{pmatrix} + e^{-\ell_r} \begin{pmatrix}
\hat{\eta}_1 \\
\hat{\eta}_2
\end{pmatrix} + \begin{pmatrix}
\hat{\xi}_1 \\
\hat{\xi}_2
\end{pmatrix}
\]

- Cross and self-phase modulation, four-wave mixing …

Drummond, Boivin, Kaertner, & Haus (mid 1990’s)

Huang & Kumar, NJP 14, 053038 (2012)

\[
\theta(t) = \frac{[\Phi_+(t) - \Phi_-(t)]}{2}
\]

\[
\Phi_{\pm}(t) = \int_0^L \left[ \xi_{||} P_{||}(z, t - L/v_s + z \beta_{\pm}) + \xi_{\perp} P_{\perp}(z, t - L/v_s + z \beta_{\pm}) \right] dz
\]
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Coincidence (Quantum) Eye Opening

Hall, Altepeter, & PK, NJP 13, 105004 (2011)

~100ps-wide Quantum Eye

Channel 1 Channel 2
Time-Domain Multiplexed Quantum Data

\[ |\Psi_1\rangle = |HH\rangle + |VV\rangle \]

\[ |\Psi_2\rangle = |HH\rangle - |VV\rangle \]

\[ |\Psi_1\rangle\langle\Psi_1| + |\Psi_2\rangle\langle\Psi_2| \]

Fidelity to \(|\alpha\beta\rangle + |\alpha^\bot\beta^\bot\rangle = 0.589\)
Time-Domain Demultiplexing of Ultrafast Quantum Channels

\[ |\Psi_1\rangle\langle\Psi_1| + |\Psi_2\rangle\langle\Psi_2| \]

Fidelity to $|\alpha\beta\rangle + |\alpha^\perp\beta^\perp\rangle = 0.589$

Hall, Altepeter, & PK, PRL 106, 053901 (2011)

Fidelity to $|\alpha\beta\rangle + |\alpha^\perp\beta^\perp\rangle = 0.986$
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**Time-Bin Qudits: Generation Setup**

\[
|\psi\rangle = \frac{1}{\sqrt{4}} (|00\rangle + |11\rangle + |22\rangle + |33\rangle)
\]

Legend:
- \(\text{PDFA}\): Praseodymium doped fiber amplifier
- \(\text{AM}\): Amplitude modulator
- \(\text{PM}\): Phase modulator
- \(\text{SMF}\): Single-mode fiber
- \(\text{DSF}\): Dispersion-shifted fiber

\[\lambda_0 = 1551 \text{ nm}\]

- **CW 1305 nm**
- **PM**
- **AM**
- **DSF 7 km**
- **AM**
- **PDFA**
- **1305 nm**
- **SMF 500 m**
- **77 K**
- **1306.5 nm**
- **1303.5 nm**

Reference:
Murata et al., IEEE STQE 6, 1325–1331 (2000)
Measurement: Qudit State Tomography

Signal photon
\[ \left\{ |t_a\rangle, |t_b\rangle, \frac{1}{\sqrt{2}} (|t_a\rangle \pm |t_b\rangle), \frac{1}{\sqrt{2}} (|t_a\rangle \pm i |t_b\rangle) \right\} \otimes \left\{ |t_a\rangle, |t_b\rangle, \frac{1}{\sqrt{2}} (|t_a\rangle \pm |t_b\rangle), \frac{1}{\sqrt{2}} (|t_a\rangle \pm i |t_b\rangle) \right\} \]
\[ t_a, t_b \in (0, \ldots, d - 1) \]

Idler photon
\[ \left\{ |H\rangle, |V\rangle, \frac{1}{\sqrt{2}} (|H\rangle \pm |V\rangle), \frac{1}{\sqrt{2}} (|H\rangle \pm i |V\rangle) \right\} \]
\[ t_a, t_b \in (0, \ldots, d - 1) \]

<table>
<thead>
<tr>
<th>(d)</th>
<th>Number of measurement settings</th>
<th>(\propto \left( \frac{d}{2} \right)^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9 (36)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>81 (324)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>324 (1296)</td>
<td></td>
</tr>
</tbody>
</table>

Measurement: Time-Bin $\rightarrow$ Polarization

signal or idler photon

Legend
- Tunable optical delay
- Polarizing beam splitter (PBS)
- 50:50 beam splitter (BS)
- Phase shifter
- Fiber polarization controller
Manipulation: Time Bin Selection

- Cross-bar optical switch that uses cross-phase modulation (XPM)

Legend:

- Tunable optical delay
- Circulator
- WDM
- BS
- FPC
- XPM pump (1550 nm)

Results: Ququart Entanglement

\[ |\psi\rangle = \frac{1}{\sqrt{4}} (|00\rangle + |11\rangle + |22\rangle + |33\rangle) \]

\[
F(\rho_{\text{exp}}, \rho_{\text{meas}}) = \left\{ \text{Tr} \left( \sqrt{\rho_{\text{exp}} \rho_{\text{meas}} \rho_{\text{exp}}} \right) \right\}^2
\]

<table>
<thead>
<tr>
<th></th>
<th>( F(\rho_{\text{exp}}, \rho_{\text{meas}}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidental coincidence subtraction</td>
<td>93.7 ± 0.4%</td>
</tr>
<tr>
<td>Background accidental coincidence subtraction</td>
<td>71.9 ± 0.3%</td>
</tr>
<tr>
<td>Minimum to violate Bell’s inequalities</td>
<td>71%</td>
</tr>
</tbody>
</table>

Nowierski, Oza, Kumar, & Kanter, PRA 94, 042328 (2016)
Conclusions / Future Outlook

- XPM based switching platform for O-band entanglement
  - High-fidelity switching of O-band entanglement in excellent agreement with theory
  - Negligible in-band noise from Raman scattering of pump
  - Demonstrated very high speed operation (10-100 GHz)
  - Demonstrated high-speed MUX / DEMUX of quantum data pattern
  - Demonstrated high-speed time-bin qudit ($d = 2, 3, 4$) tomography
  - Potentially very low loss (< 0.2-0.3 dB per switching cycle)
- Short-term (10’s to 100’s µs) quantum buffers and single-photons on demand are a practical near-term reality