All-optical Switching for Photonic Quantum Networks

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Classical vs. Quantum Communication

Classical bit: 0 or 1

Alice

Error-free communication below channel capacity

Bob

Quantum bit:

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

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

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*

Alice

Transmitter T and Receiver R share entangled qubits

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

Bob

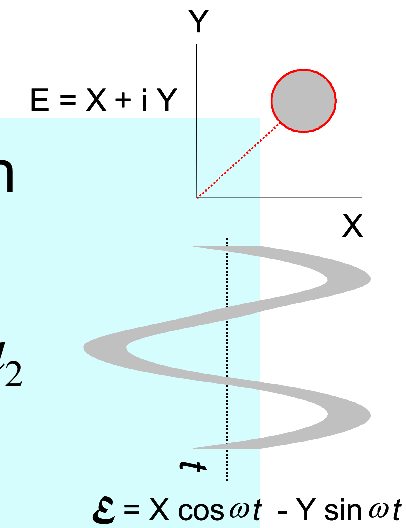
- $|\Psi\rangle_{in} = \alpha|0\rangle_{in} + \beta|1\rangle_{in}$ Transmitter accepts input qubit and makes measurements on the joint state of the input qubit and Transmitter's part of the entangled qubit

- Measurement results (two classical bits) sent to Receiver

- Simple transformation at Receiver yields $|\Psi\rangle_R = \alpha|0\rangle_R + \beta|1\rangle_R$

* Bennett *et al*. "Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels," Phys. Rev. Lett. **70**, 1895–1899 (1993).

Analog (CV) Quantum Information



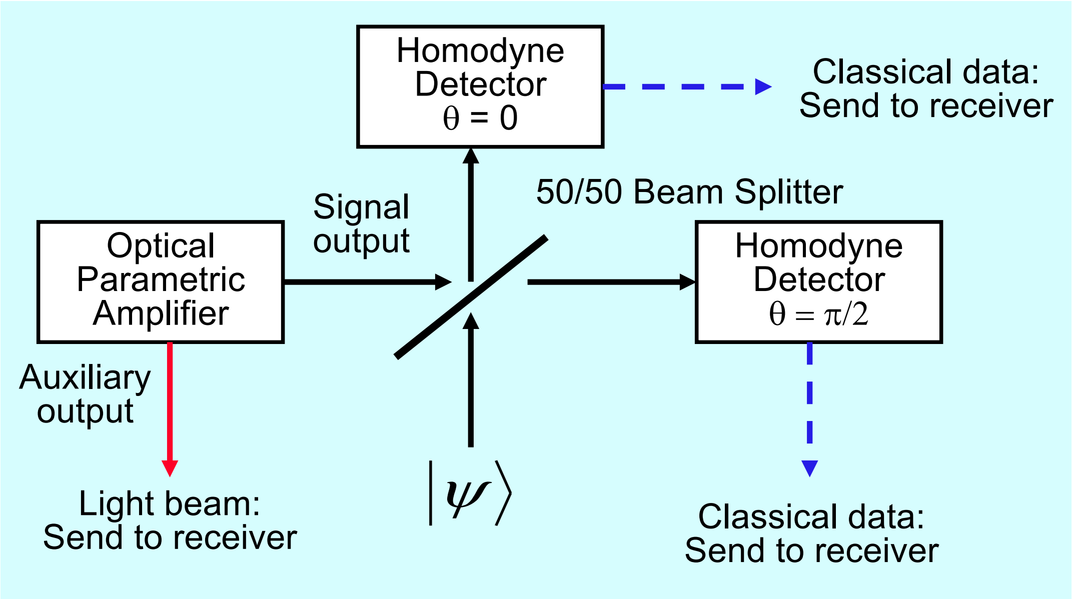
- Classical EM-field supports noiseless oscillation
  - Phasor representation of single mode: $a\, e^{-i\omega t}$
  - Quadrature representation of the phasor: $a = a_1 + i a_2$
- Quantum EM-field obeys uncertainty principle
  - Operator representation of single mode: $\hat{a}\, e^{-i\omega t}$
  - Quadrature 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:

$\left\langle \left(\Delta\hat{a}_{S_1} - \Delta\hat{a}_{I_1}\right)^2 \right\rangle = s/4$ and $\left\langle \left(\Delta\hat{a}_{S_2} + \Delta\hat{a}_{I_2}\right)^2 \right\rangle = s/4$, where $s < 1$

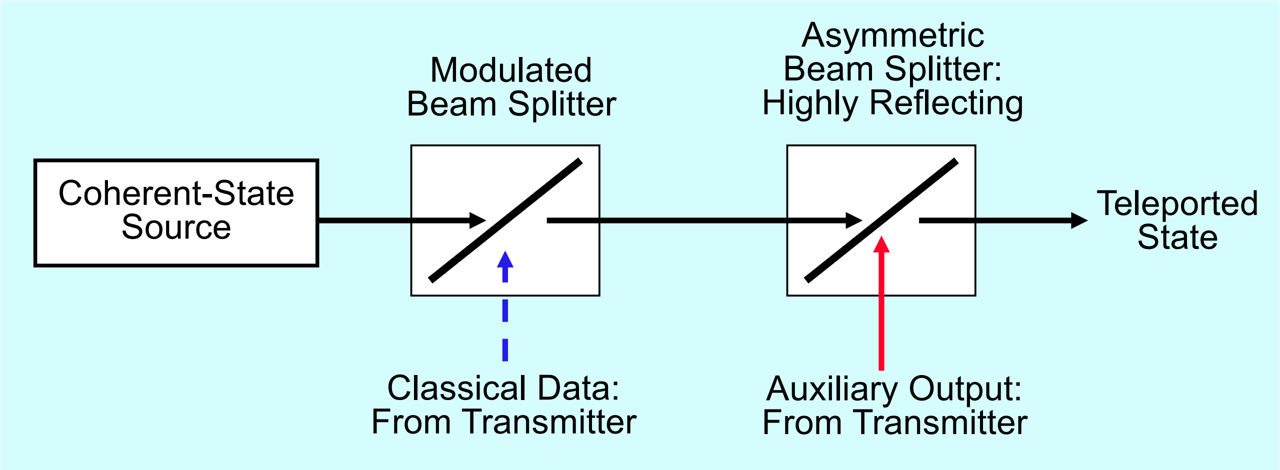
CV = continuous variable; EM = electromagnetic; OPA = optical parametric amplifier

Teleportation via Field Quadratures*

- Transmitter Station



- Receiver Station



* Braunstein and Kimble, "Teleportation of continuous quantum variables," PRL **80**, 869 (1998).
Furusawa *et al.*, "Unconditional quantum teleportation," Science **282**, 706–709 (1998).

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

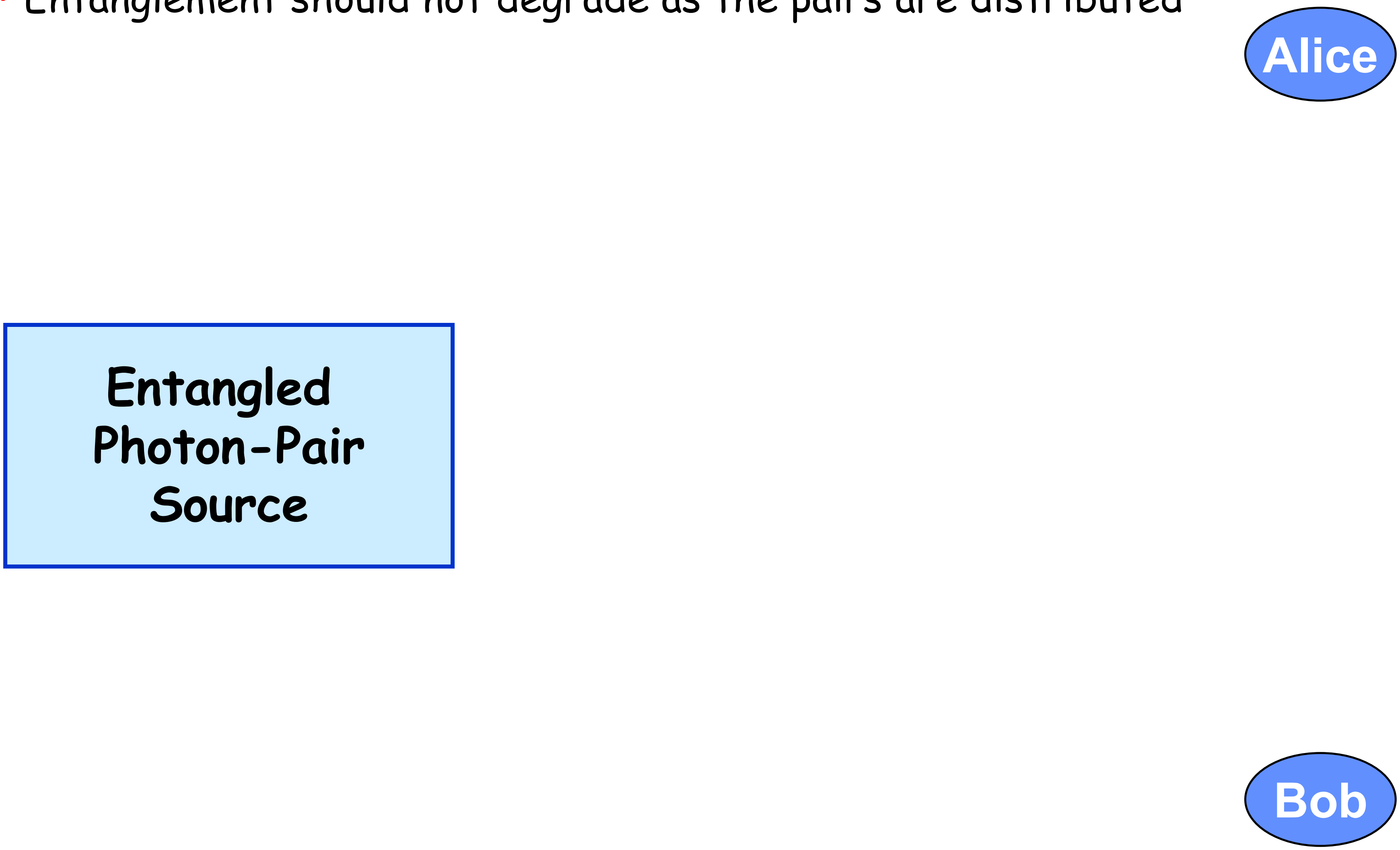
QC: Sending quantum information between two or more quantum nodes

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



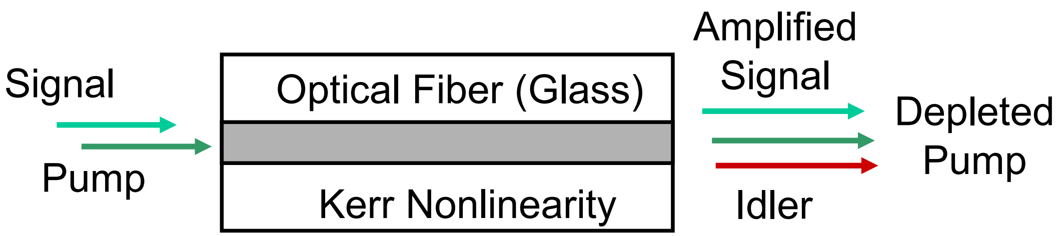
Progress Towards Practical Quantum Communications

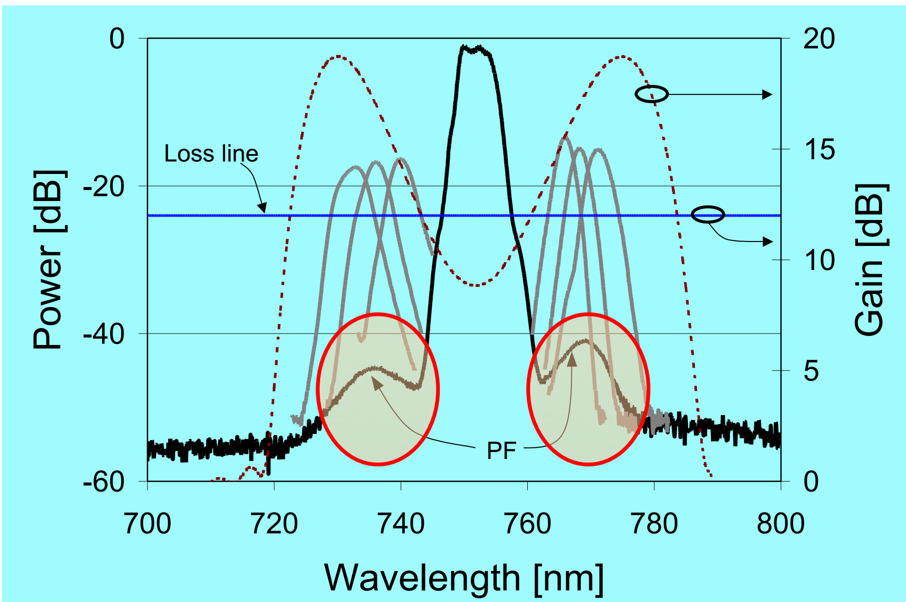
- Near infrared systems based on $\chi^{(2)}$ crystals, bulk as well as waveguide

- 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



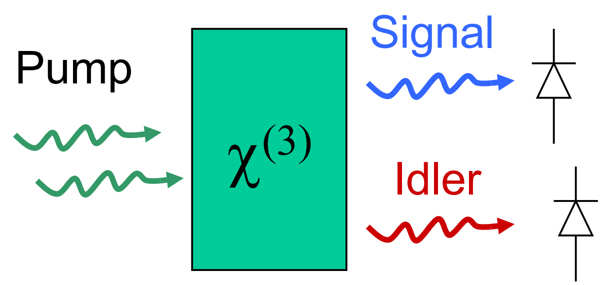


Sharping et al., Opt. Lett. ***27****, 1675 (2002)*

Strong parametric fluorescence is easily observed at moderate pump power

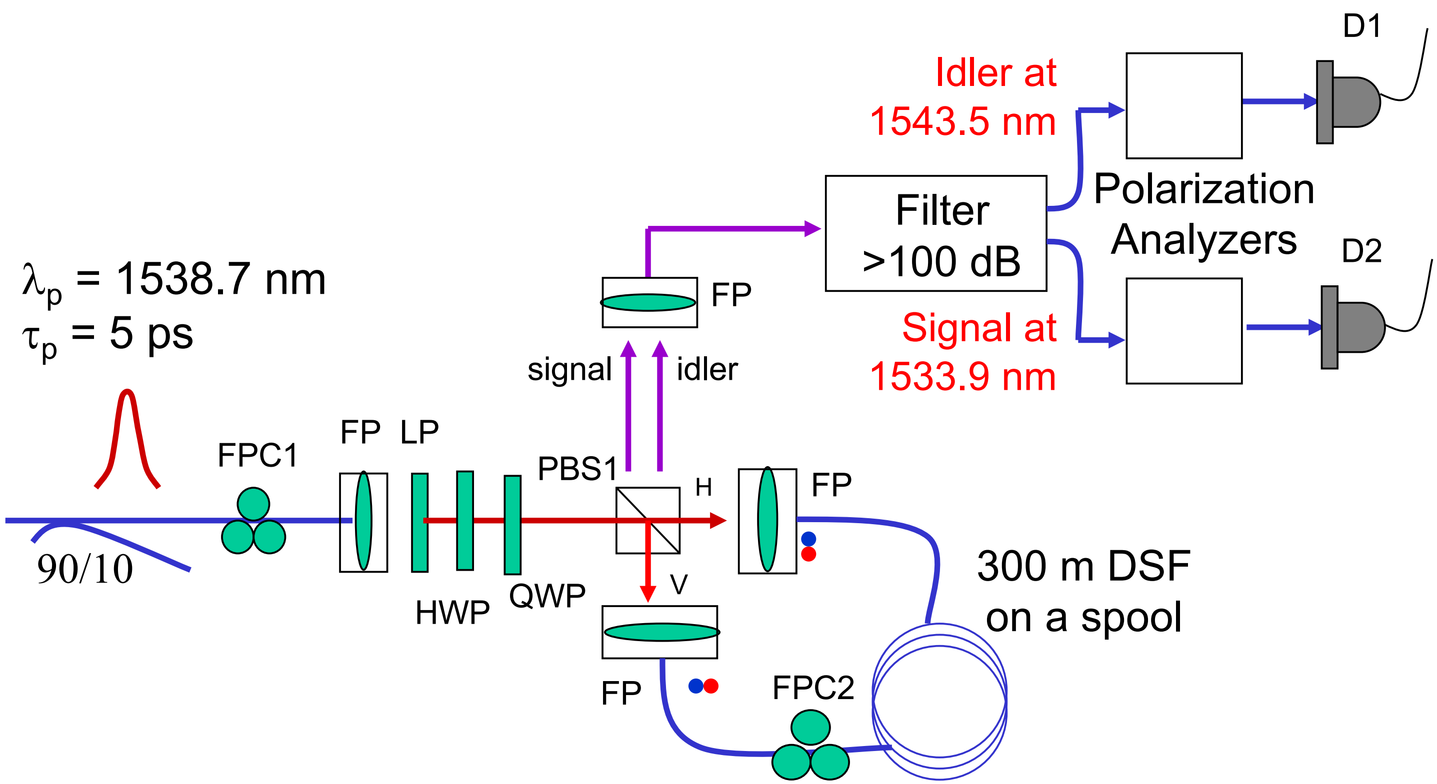
At the Quantum Level:

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

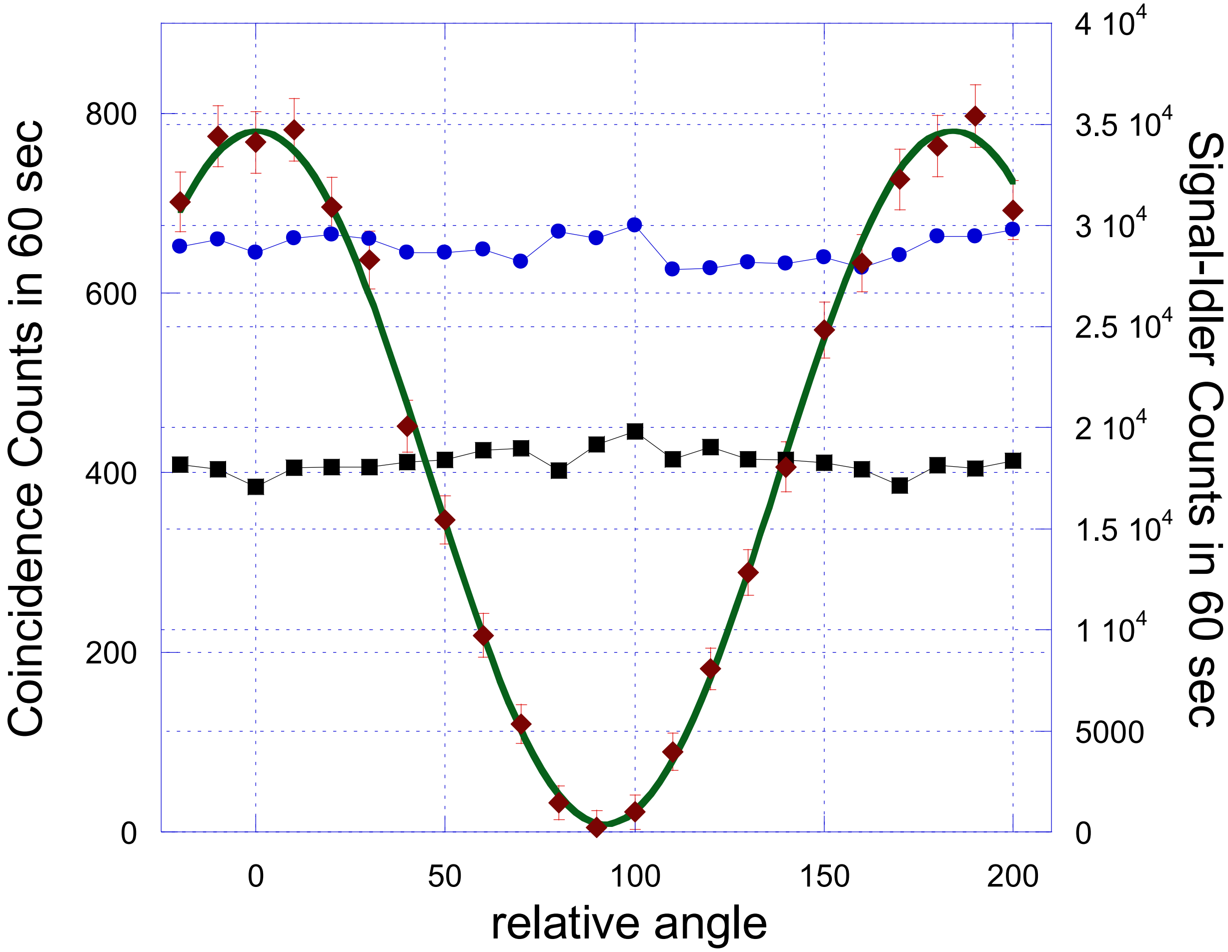


M. Fiorentino *et al.*, IEEE PTL **14**, 983 (2002)
X. Li *et al.*, PRL **94**, 053601 (2005)

Fiber-Based Source of Polarization-Entangled Photons

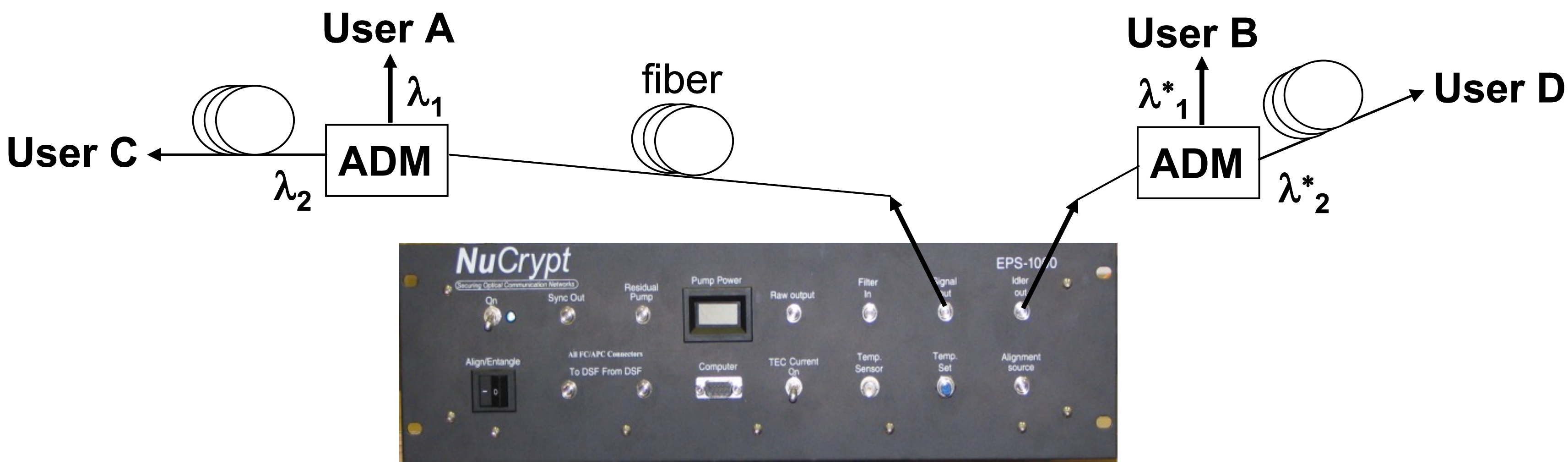


High-Purity Polarization Entanglement

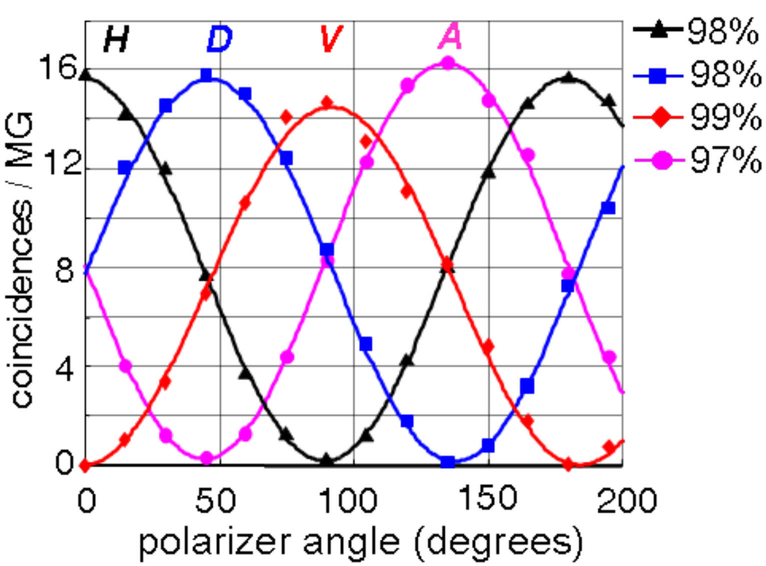


K. F. Lee, J. Chen, C. Liang, X. Li, P. L. Voss, and P. Kumar, Optics Letters 31, 1905 (2006).

Practical Source Available from NuCrypt LLC, Evanston, IL



TPI at 4 different bases, –196°C



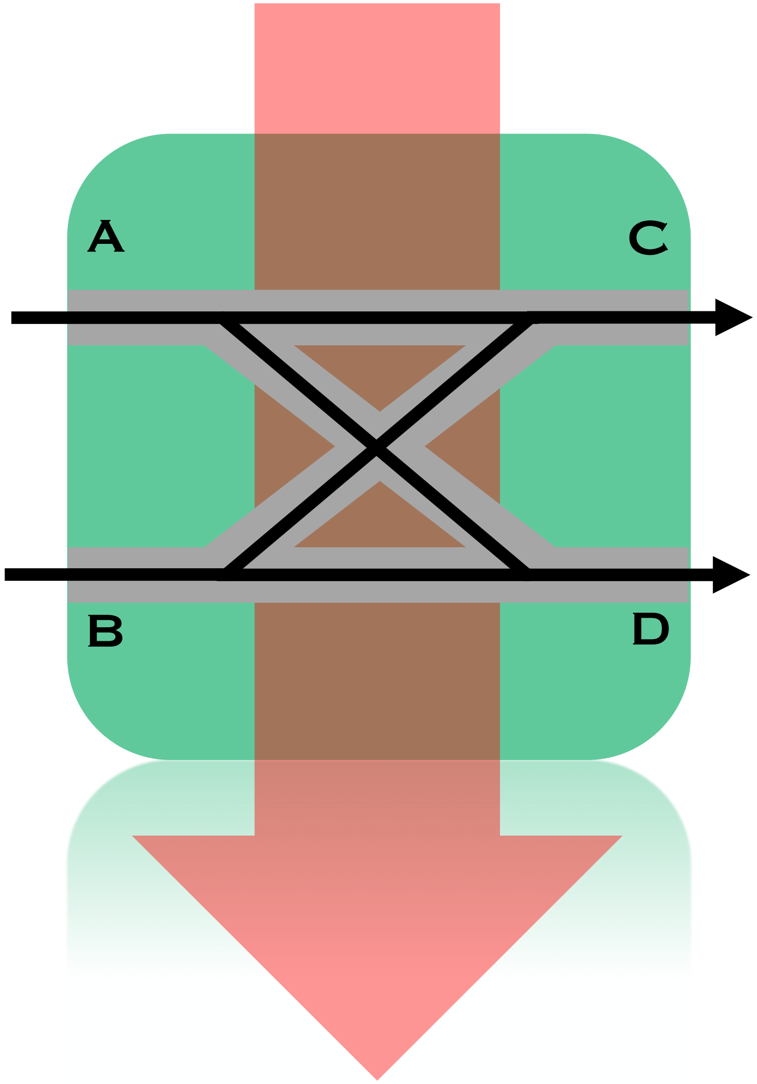
OFC-2009 Postdeadline Paper PDPA3
Multi-Channel Fiber-Based Source of Polarization Entangled Photons with Integrated Alignment Signal

Contact: kanterg@nucrypt.net

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

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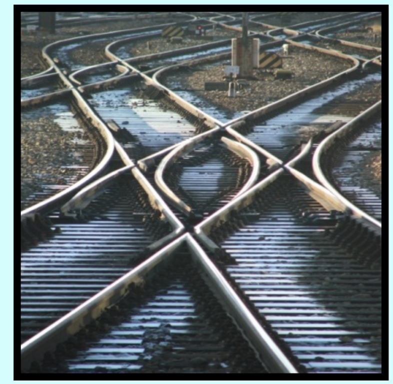
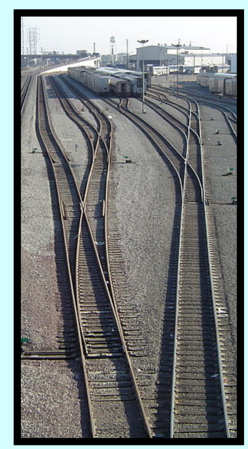
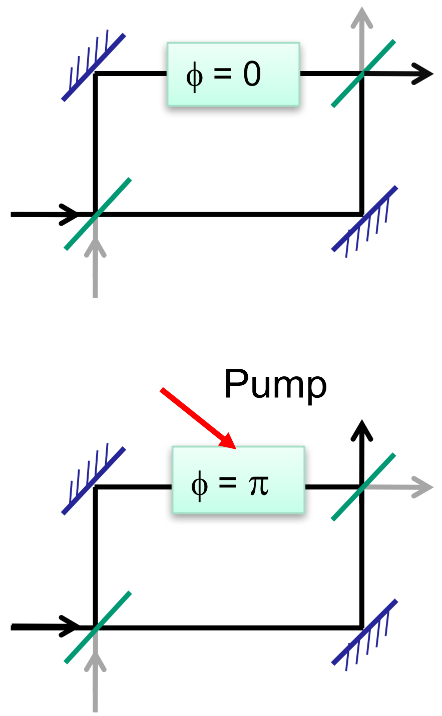




Quantum Switch Design based on Cross-Phase Modulation (XPM) in Fiber



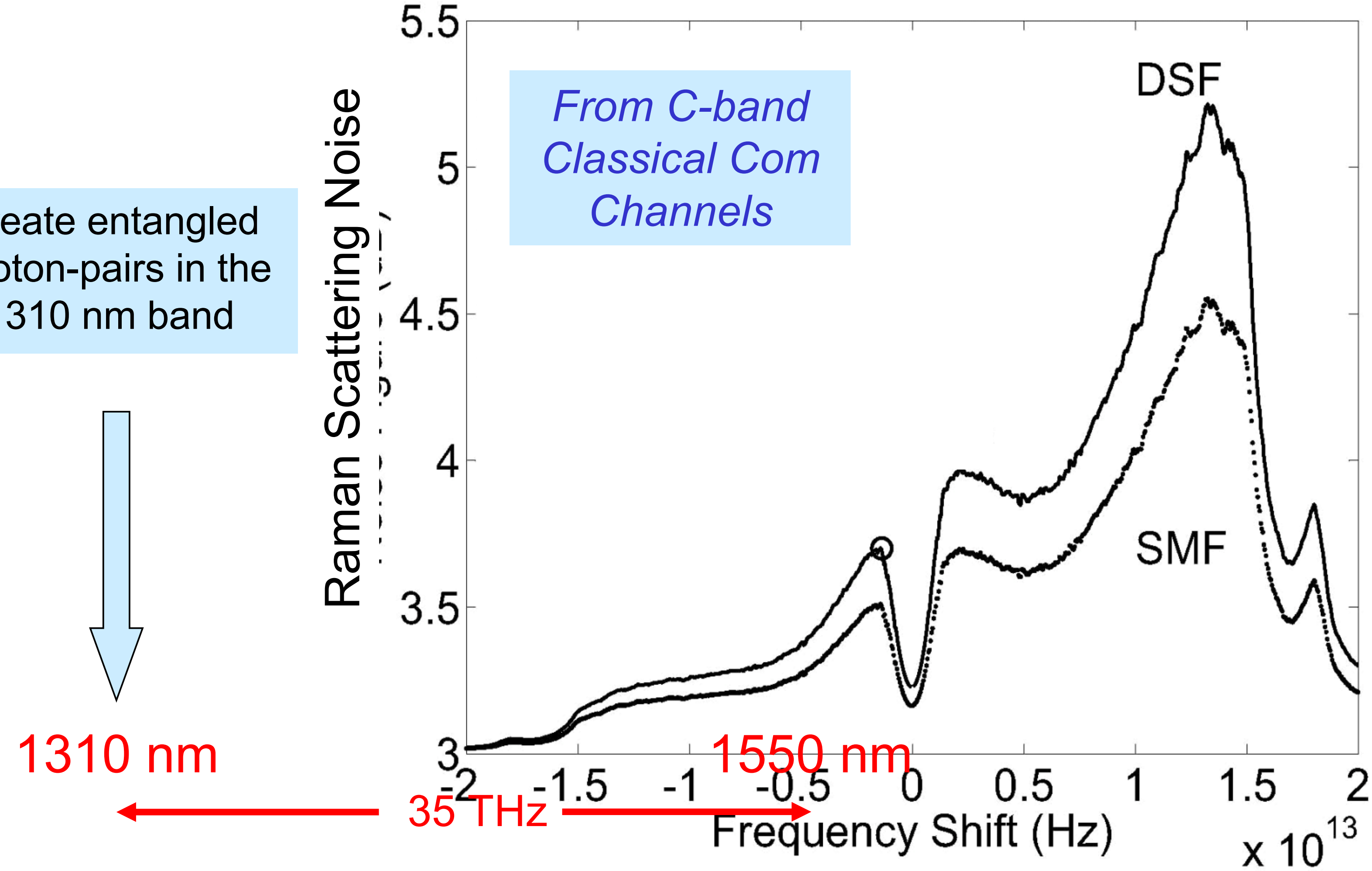
Unitary evolution in absence of Raman

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

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



Nweke *et al.*, Appl. Phys. Lett. **87**, 174103 (2005)

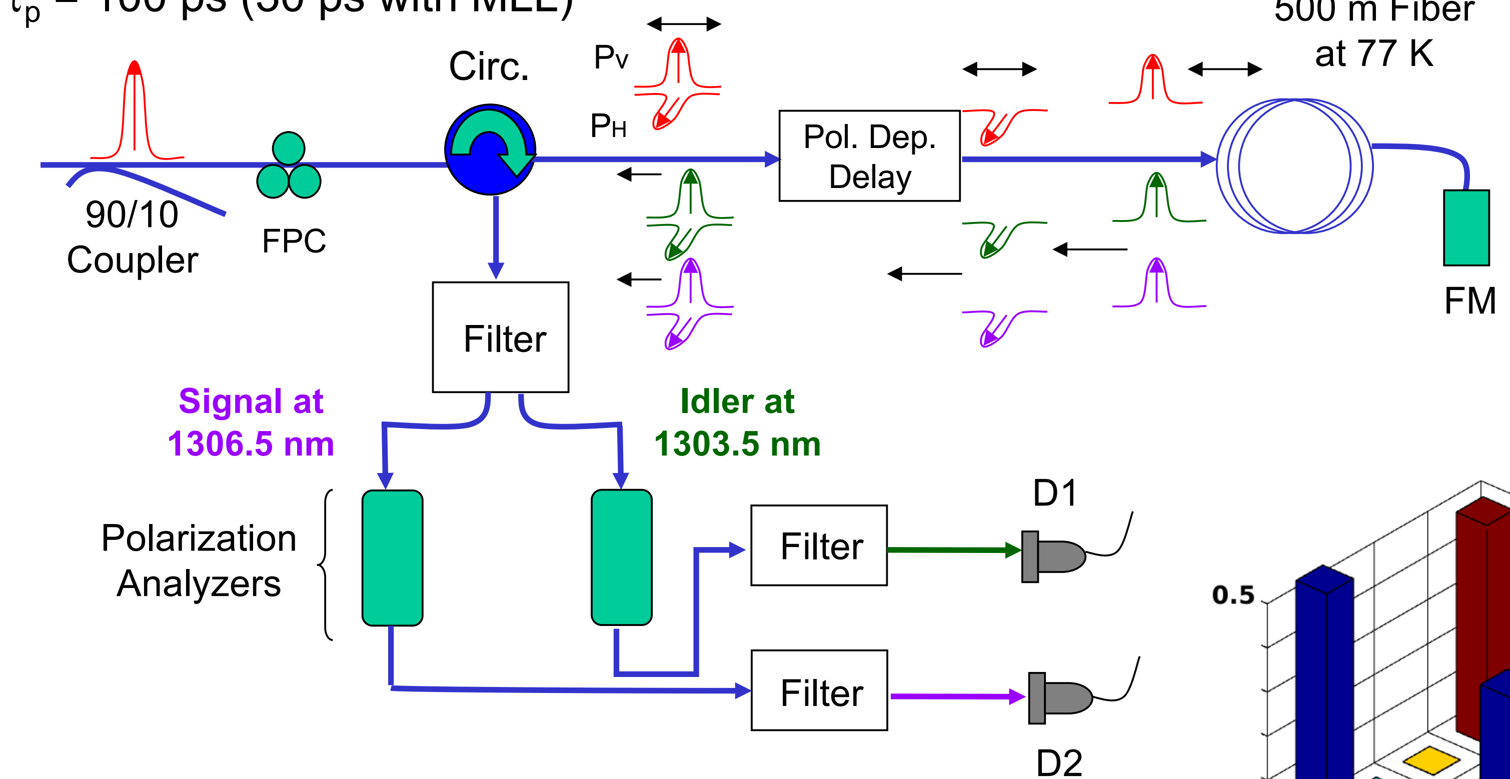
Ultrafast Entanglement Generation

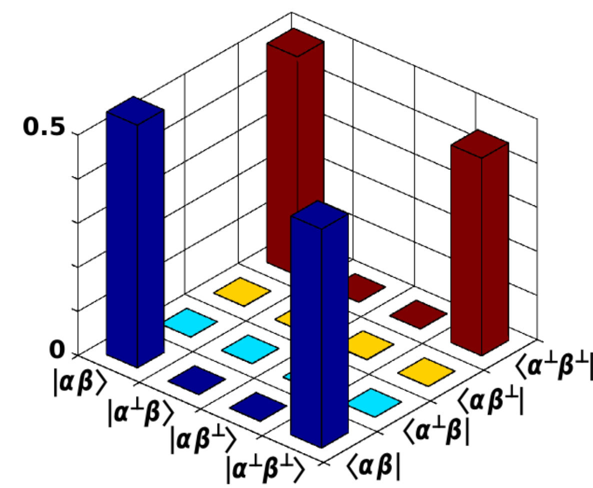
Pulses carved from a CW or ML laser

Hall, Altepeter, & PK, OpEx **17**, 14558 (2009)

λ_p = 1305 nm

τ_p = 100 ps (30 ps with MLL)

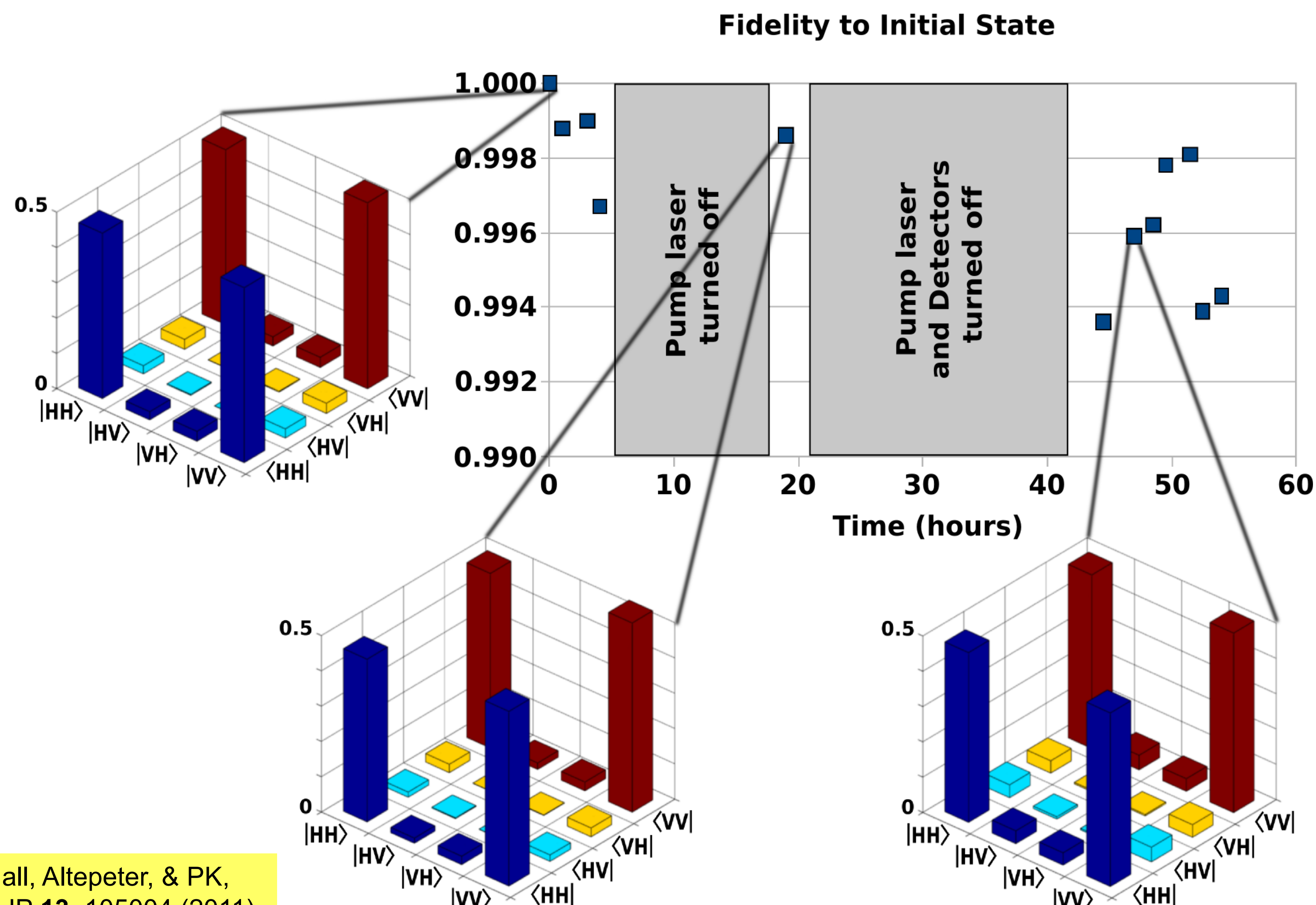




- 1.5 nm detuning from pump
  - Reduced spontaneous Raman scattering
- Mode-locked (ML) laser allows 10 GHz Operation

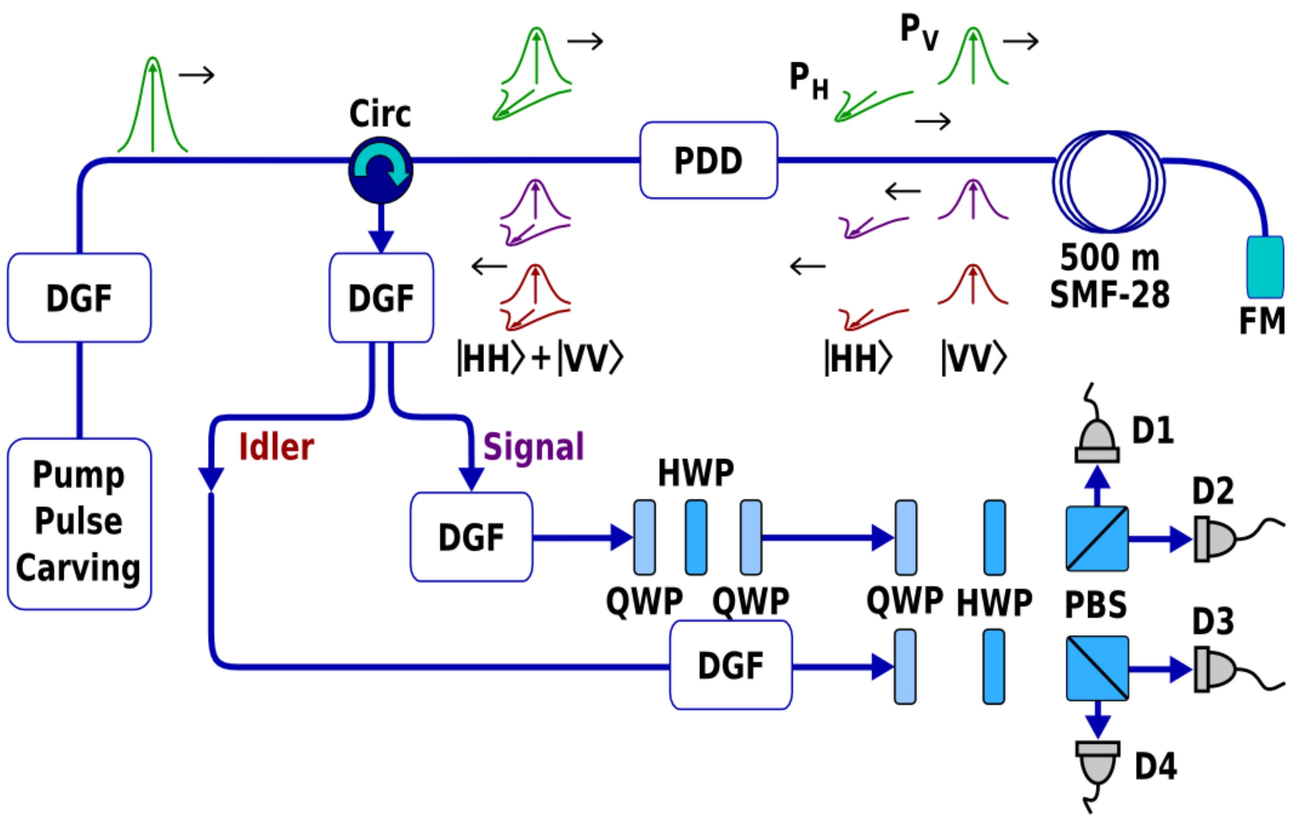
F = 99.6 ± 0.15%

Source Stability Testing

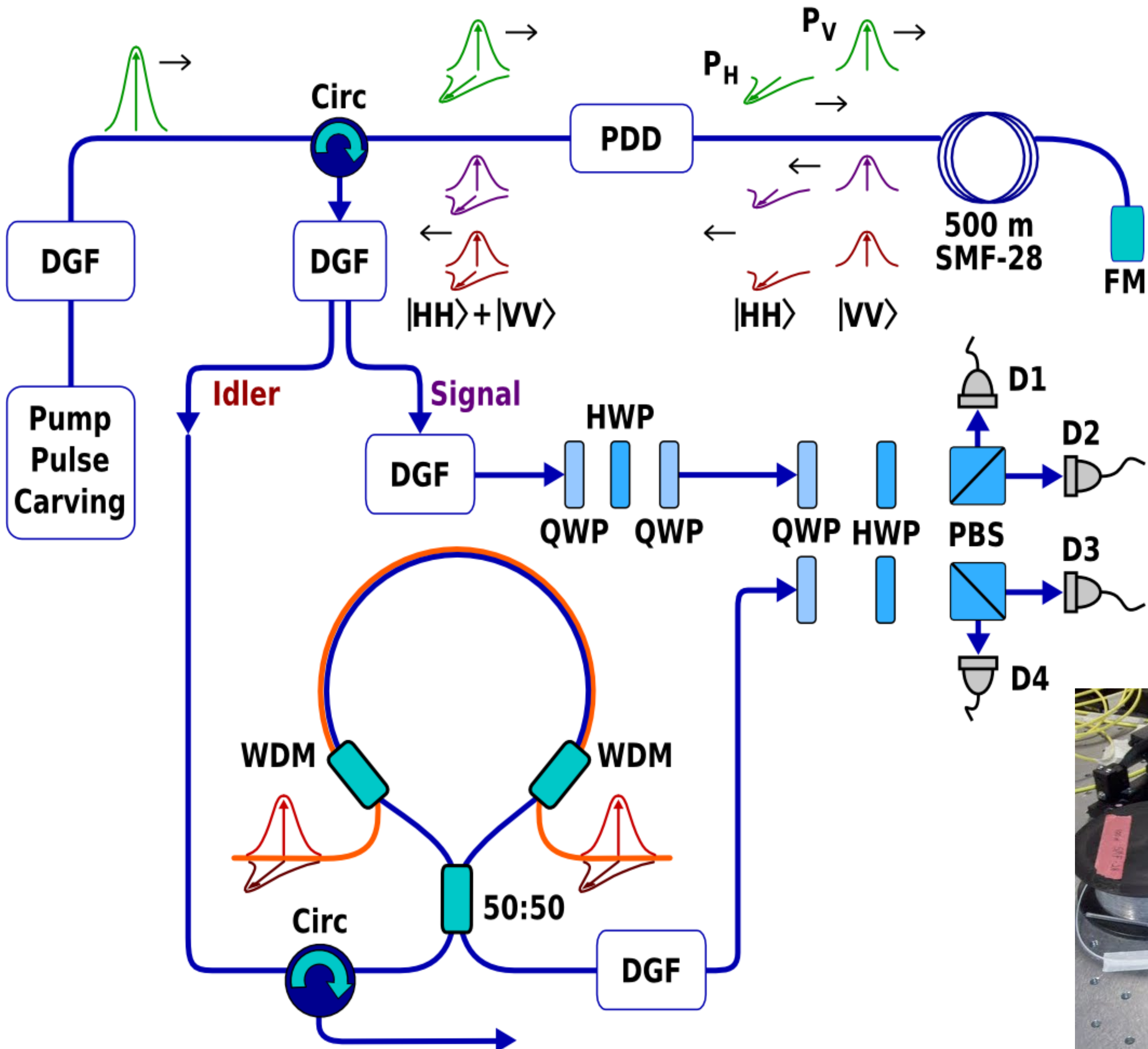


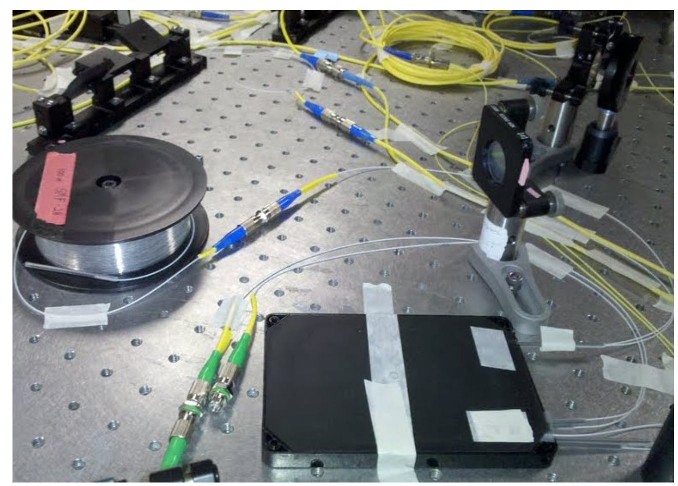
Hall, Altepeter, & PK, NJP **13**, 105004 (2011)

Switch Location for Quantum Testing



Switch Location for Quantum Testing

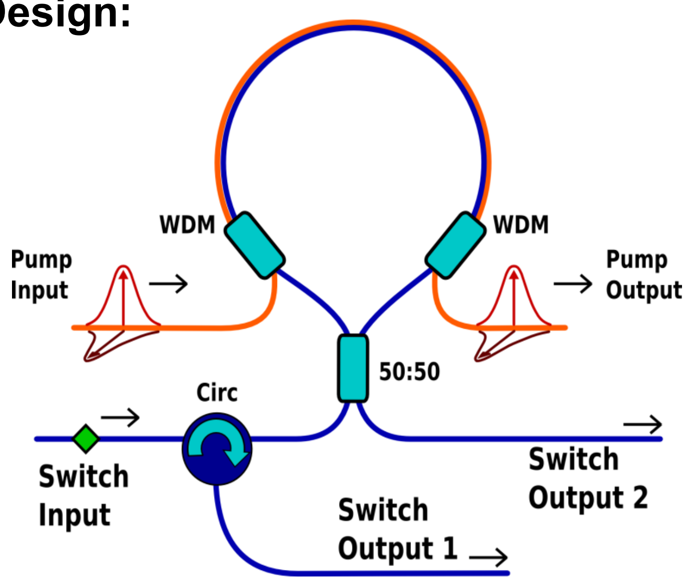




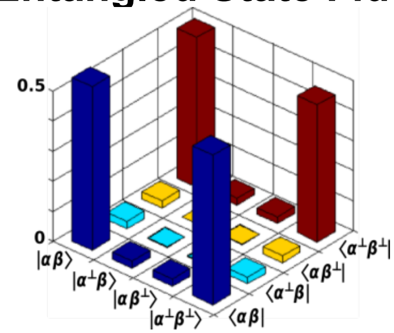
Ultrafast Switching of Photonic Entanglement

CPCC

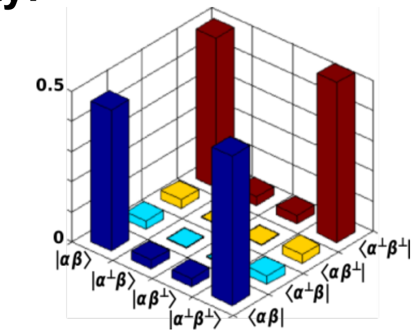
Design:



Entangled State Fidelity:



Passively Switched
F = 99.6%



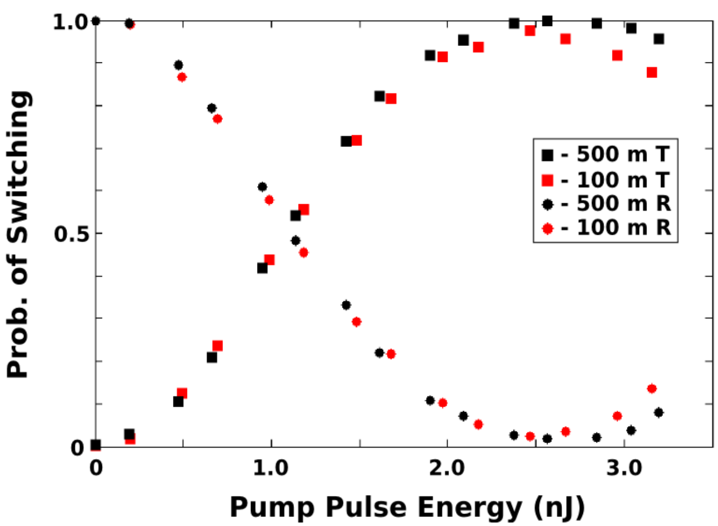
Actively Switched
F = 99.4%

Loss:

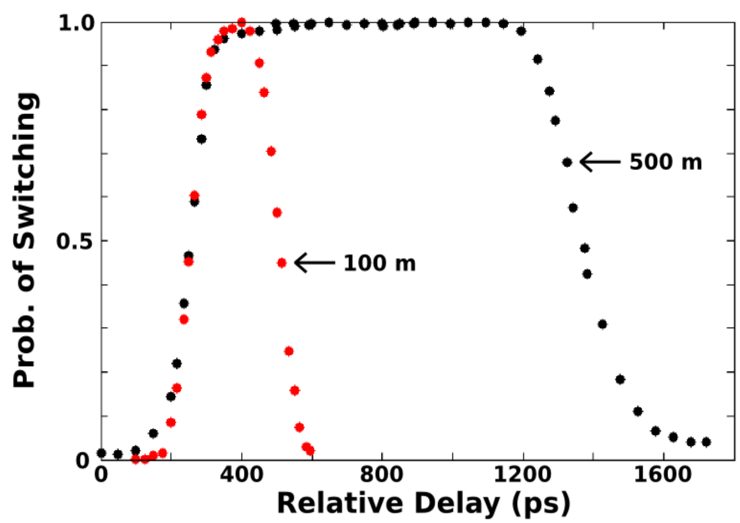
Switch	0.9 dB
Circulator	0.4 dB

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

Switching Contrast: 200-to-1

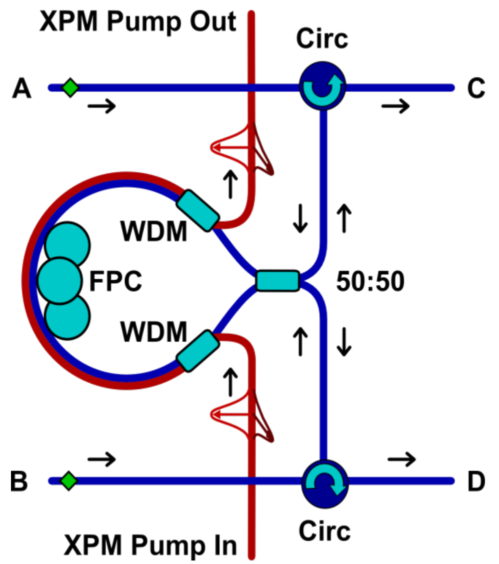


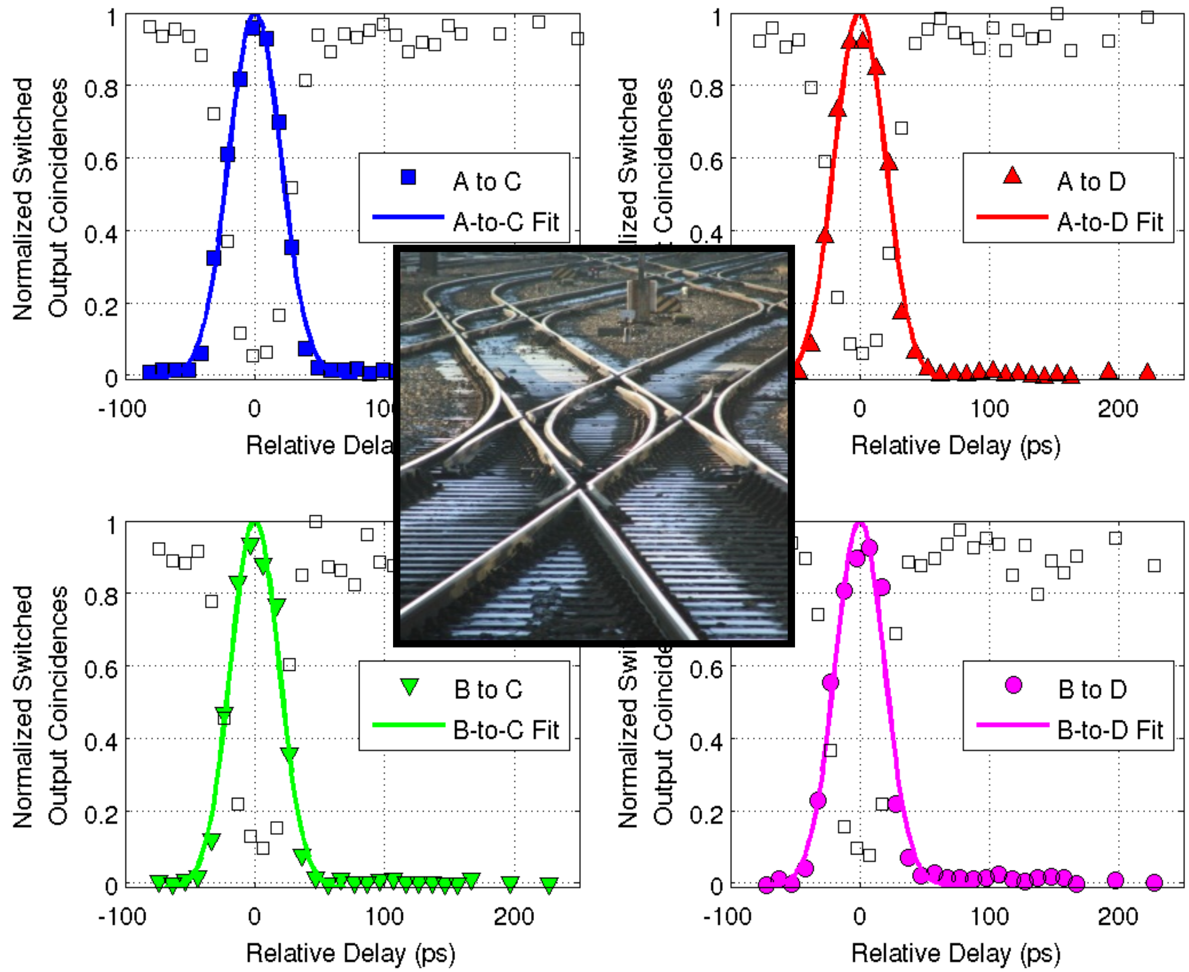
Switching Window: 850 ps (500 m); 170 ps (100m)



Full Cross-Bar Operation: Coincidence Switching Windows

Oza, Huang, & PK, IEEE PTL **26**, 356–359 (2014)





20-m Common Fiber
- ~40-ps Window

Quantum Theory of Kerr Switching

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

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

Chromatic dispersion, propagation loss, …

Spontaneous Raman scattering

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

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

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

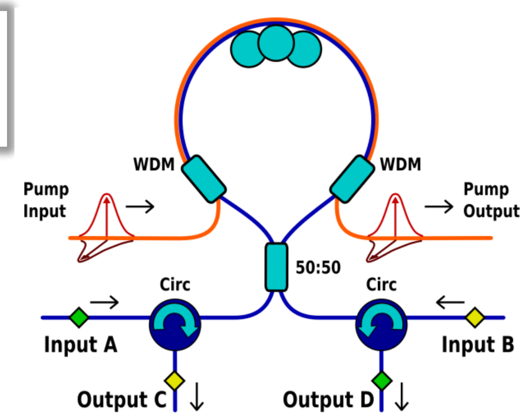
Linear loss · Coherent transformation · Ramon noise · Other quantum noise

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

Huang & Kumar,
NJP **14**, 053038 (2012)

$$\theta(t) = [\Phi_+(t) - \Phi_-(t)]/2$$

$$\Phi_{\pm}(t) = \int_0^L \left[\xi_{\parallel}P_{\parallel}(z, t - L/v_s + z\beta_{\pm}) + \xi_{\perp}P_{\perp}(z, t - L/v_s + z\beta_{\pm})\right]dz$$



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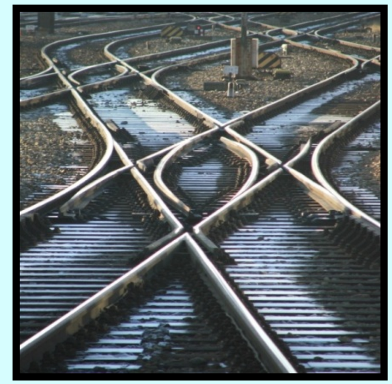
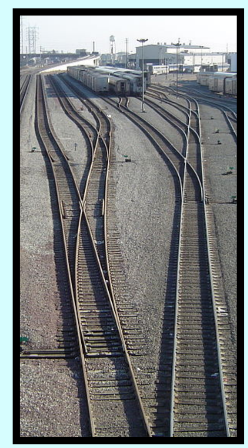
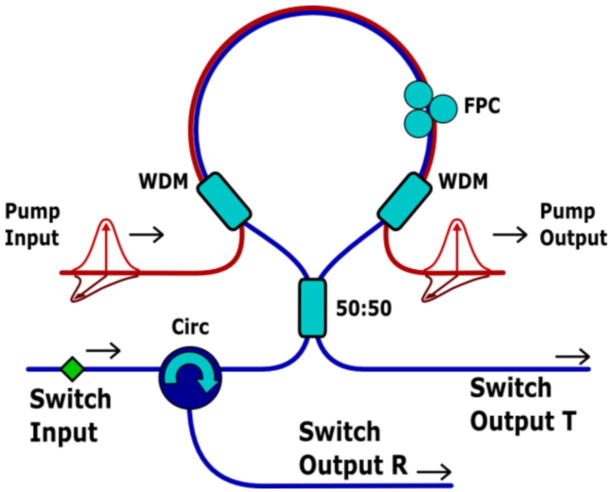
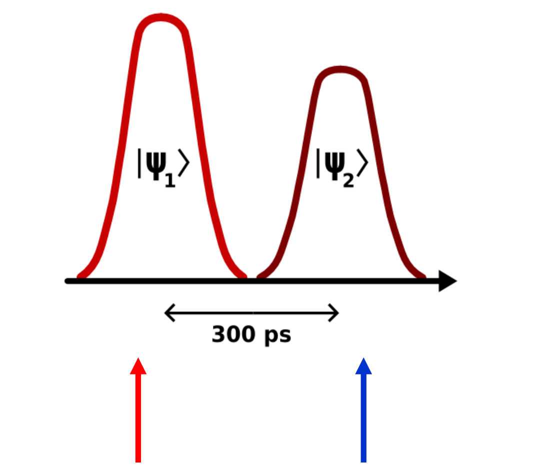




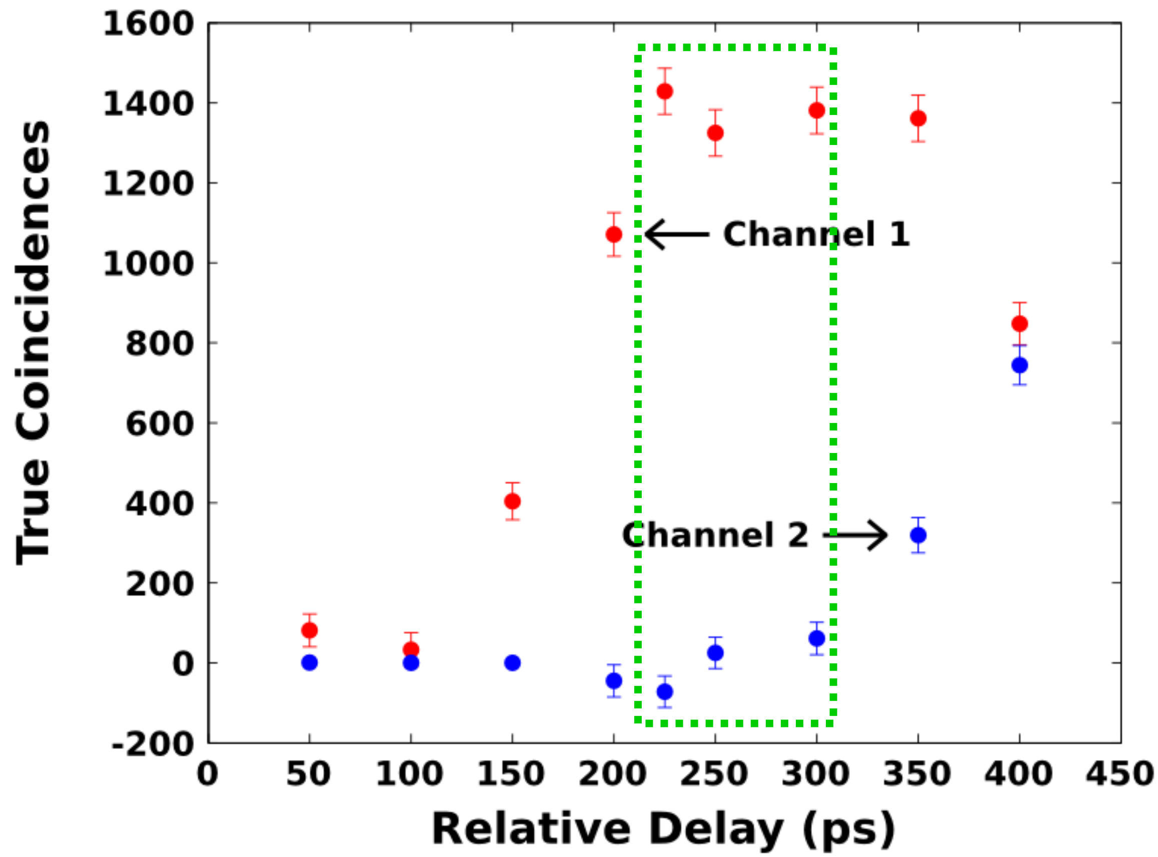
Coincidence (Quantum) Eye Opening

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

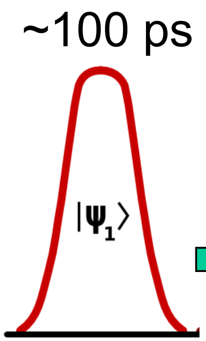




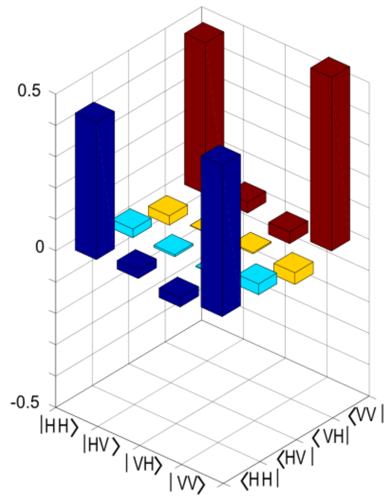
~100ps-wide
Quantum Eye

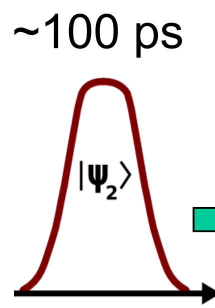


Time-Domain Multiplexed Quantum Data

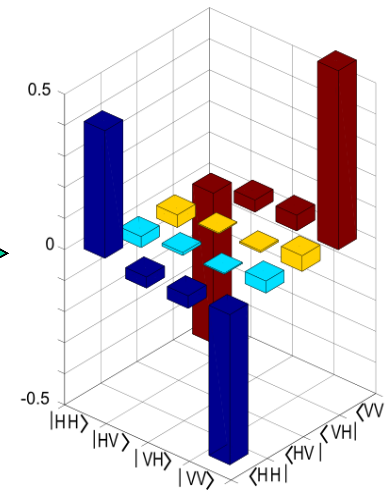


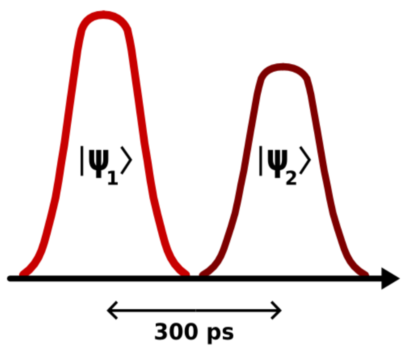
$$|\Psi_1\rangle = |HH\rangle + |VV\rangle$$



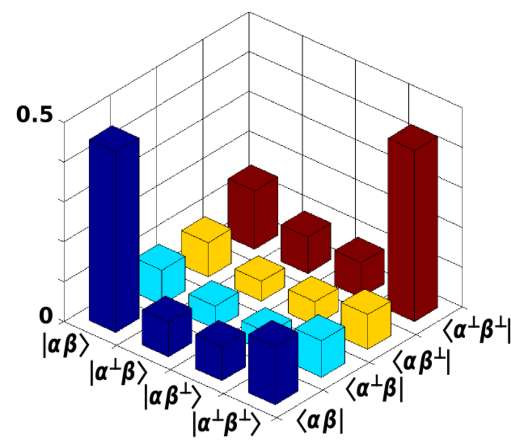


$$|\Psi_2\rangle = |HH\rangle - |VV\rangle$$



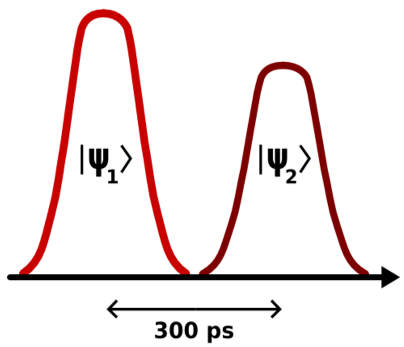


$$|\Psi_1\rangle\langle\Psi_1| + |\Psi_2\rangle\langle\Psi_2|$$

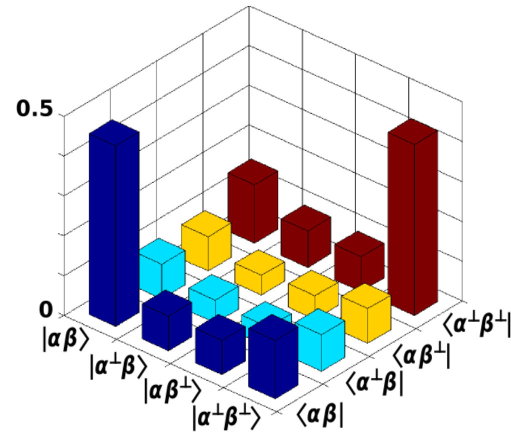


Fidelity to $|\alpha\beta\rangle + |\alpha^{\perp}\beta^{\perp}\rangle$ = 0.589

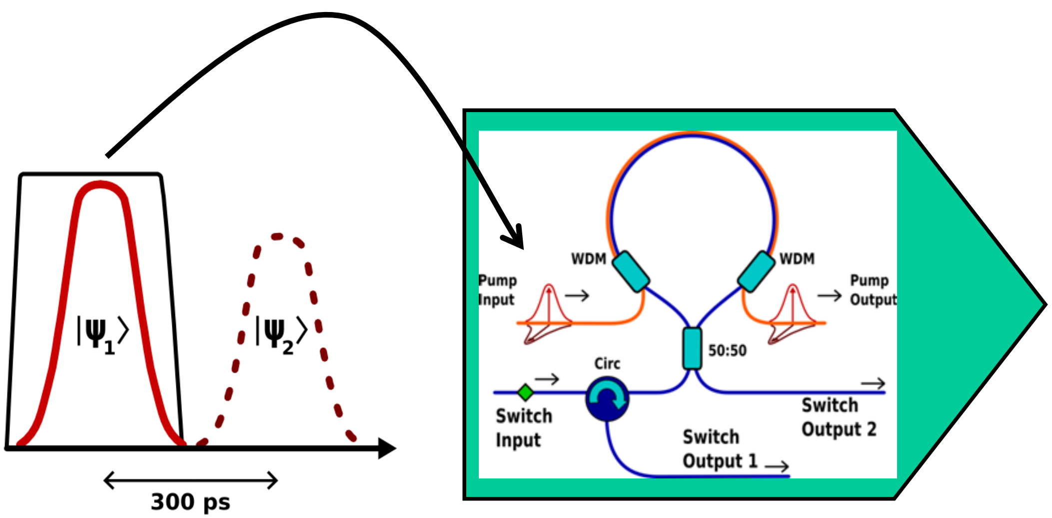
Time-Domain Demultiplexing of Ultrafast Quantum Channels

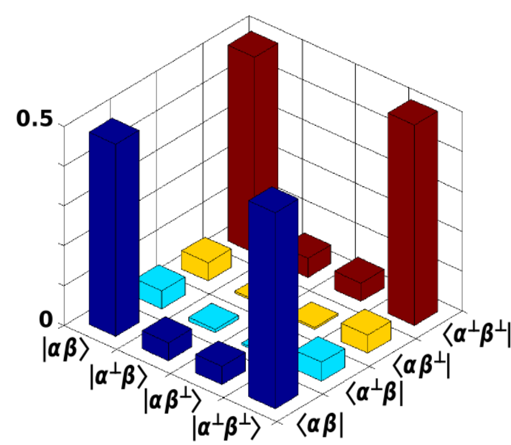


$$|\Psi_1\rangle\langle\Psi_1| + |\Psi_2\rangle\langle\Psi_2|$$



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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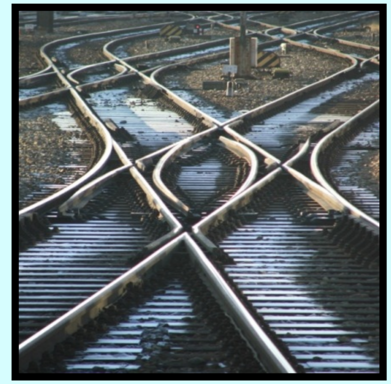
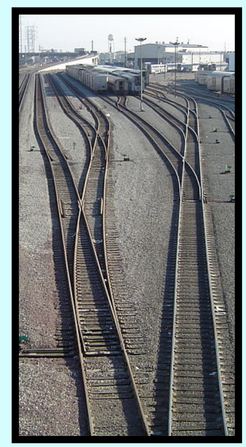
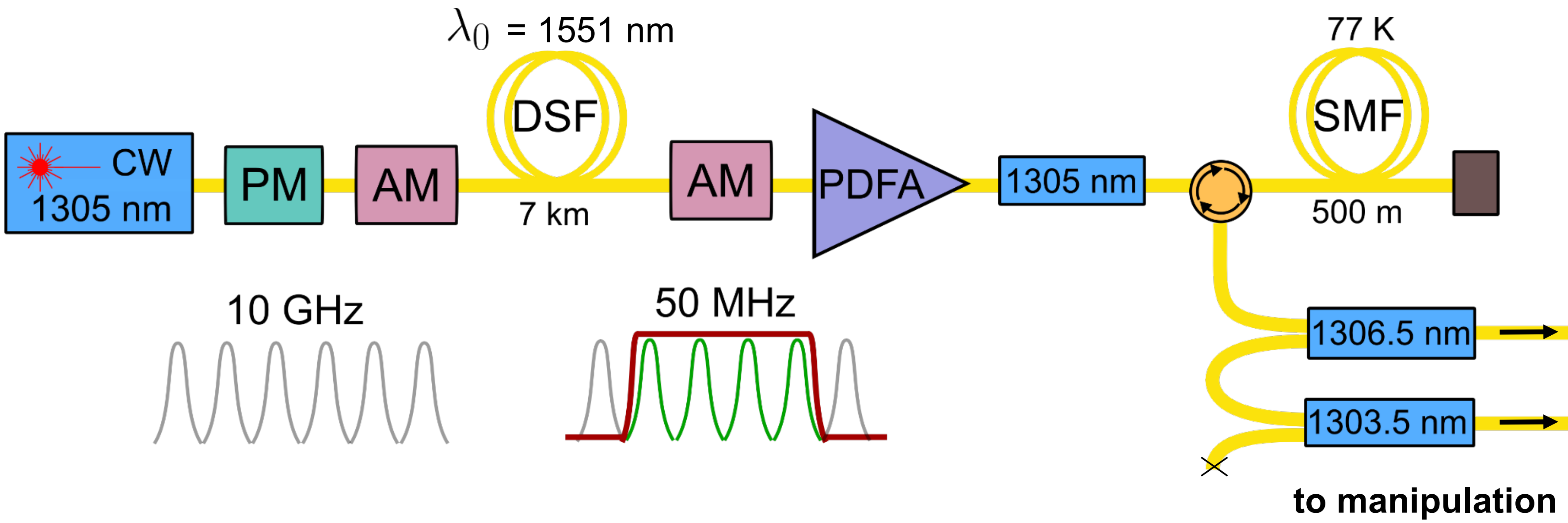




Time-Bin Qudits: Generation Setup

CPCC



$$|\psi\rangle = \frac{1}{\sqrt{4}}\left(|00\rangle + |11\rangle + |22\rangle + |33\rangle\right)$$

Legend

PDFA Praseodynmium doped fiber amplifier | Faraday mirror | Circulator | AM Amplitude modulator

Wavelength-division multiplexer (WDM) | PM Phase modulator

Murata *et al,* IEEE STQE 6, 1325–1331 (2000)

Measurement: Qudit State Tomography

Signal photon

$$\left\{ |t_a\rangle, |t_b\rangle, \frac{1}{\sqrt{2}}(|t_a\rangle \pm |t_b\rangle), \frac{1}{\sqrt{2}}(|t_a\rangle \pm i|t_b\rangle) \right\}$$

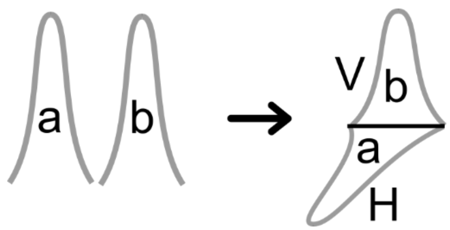
$$t_a, t_b \in (0, \ldots, d-1)$$

$\otimes$

Idler photon

$$\left\{ |t_a\rangle, |t_b\rangle, \frac{1}{\sqrt{2}}(|t_a\rangle \pm |t_b\rangle), \frac{1}{\sqrt{2}}(|t_a\rangle \pm i|t_b\rangle) \right\}$$

$$t_a, t_b \in (0, \ldots, d-1)$$

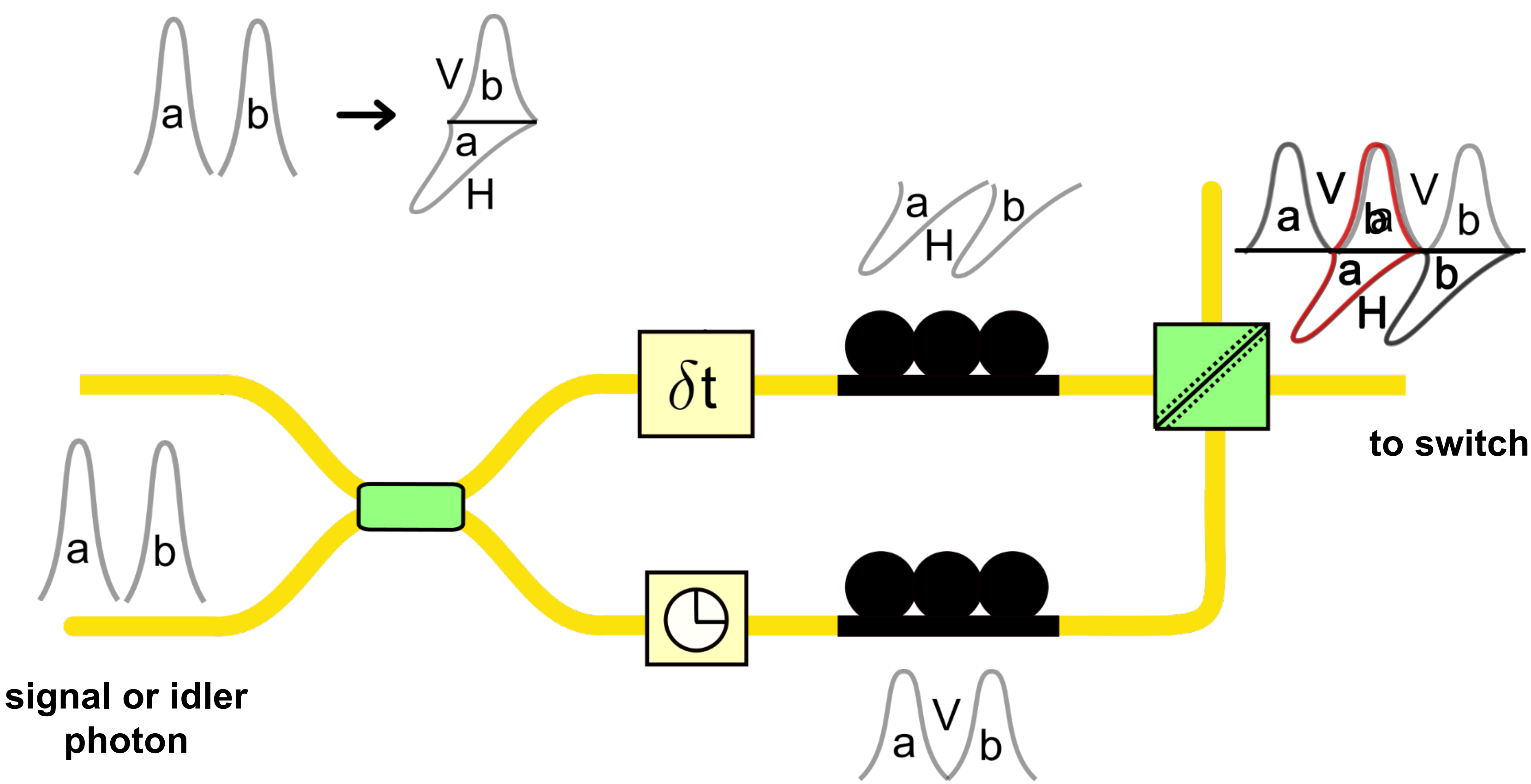


$$\left\{ |H\rangle, |V\rangle, \frac{1}{\sqrt{2}}(|H\rangle \pm |V\rangle), \frac{1}{\sqrt{2}}(|H\rangle \pm i|V\rangle) \right\}$$

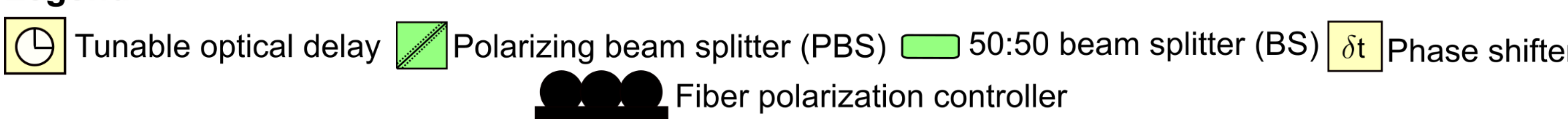
d	**Number of measurement settings** $\propto \binom{d}{2}^2$
2	9 (36)
3	81 (324)
4	324 (1296)

Thew *et al.*, Phys. Rev. A 66, 012303 (2002)

Measurement: Time-Bin → Polarization

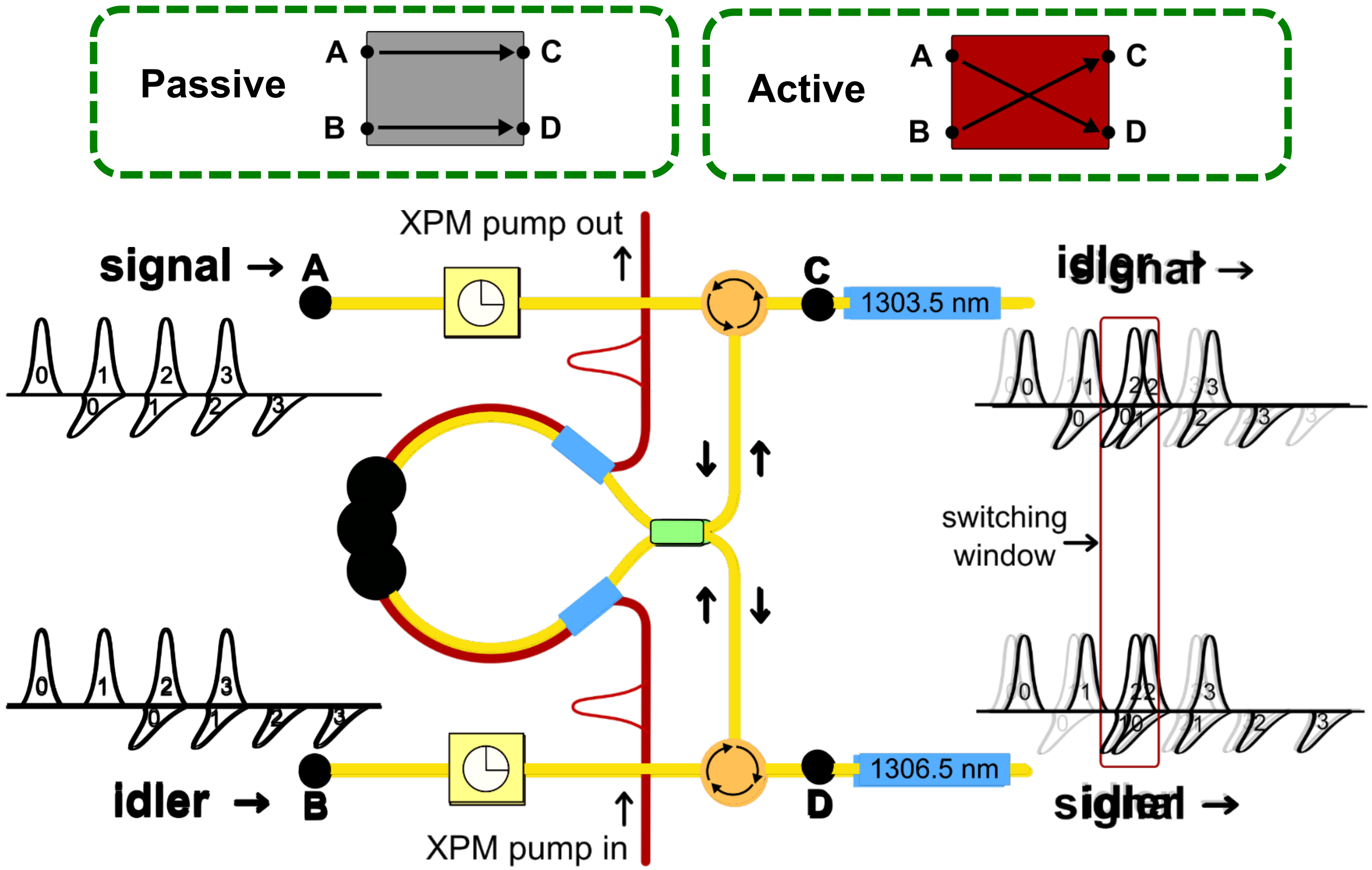


Legend



Manipulation: Time Bin Selection

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



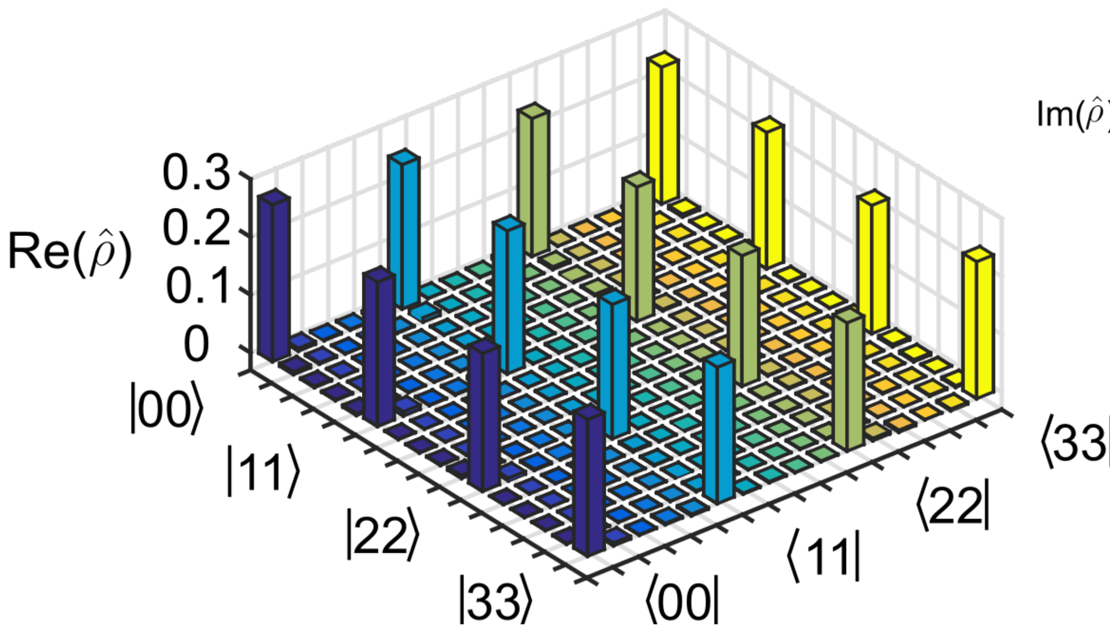
Legend

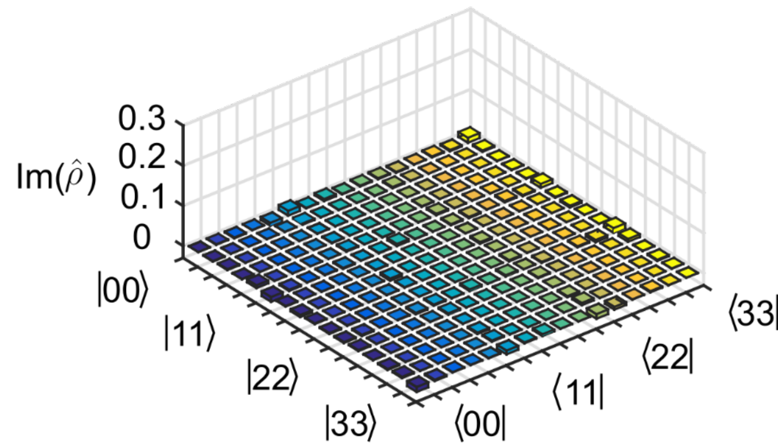
Tunable optical delay   Circulator   WDM   BS   FPC   XPM pump (1550 nm)

Oza, Huang, & Kumar, IEEE Phot. Tech. Lett. 26, 356-359 (2014)

Results: Ququart Entanglement

$$|\psi\rangle = \frac{1}{\sqrt{4}}\left(|00\rangle + |11\rangle + |22\rangle + |33\rangle\right)$$





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

	$F(\rho_{\text{exp}}, \rho_{\text{meas}})$
Accidental coincidence subtraction	**93.7 ± 0.4%**
Background accidental coincidence subtraction	**71.9 ± 0.3%**
Minimum to violate Bell's inequalities	**71%**

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