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Keynote Speech
21 November 2011

Engineering Quantum Communications for the Telecom Band

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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*

Transmitter T and Receiver R share entangled qubits

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

Alice

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-Podolssky-Rosen channels" Phys. Rev. Lett., **70**, 1895--1899 (1993).

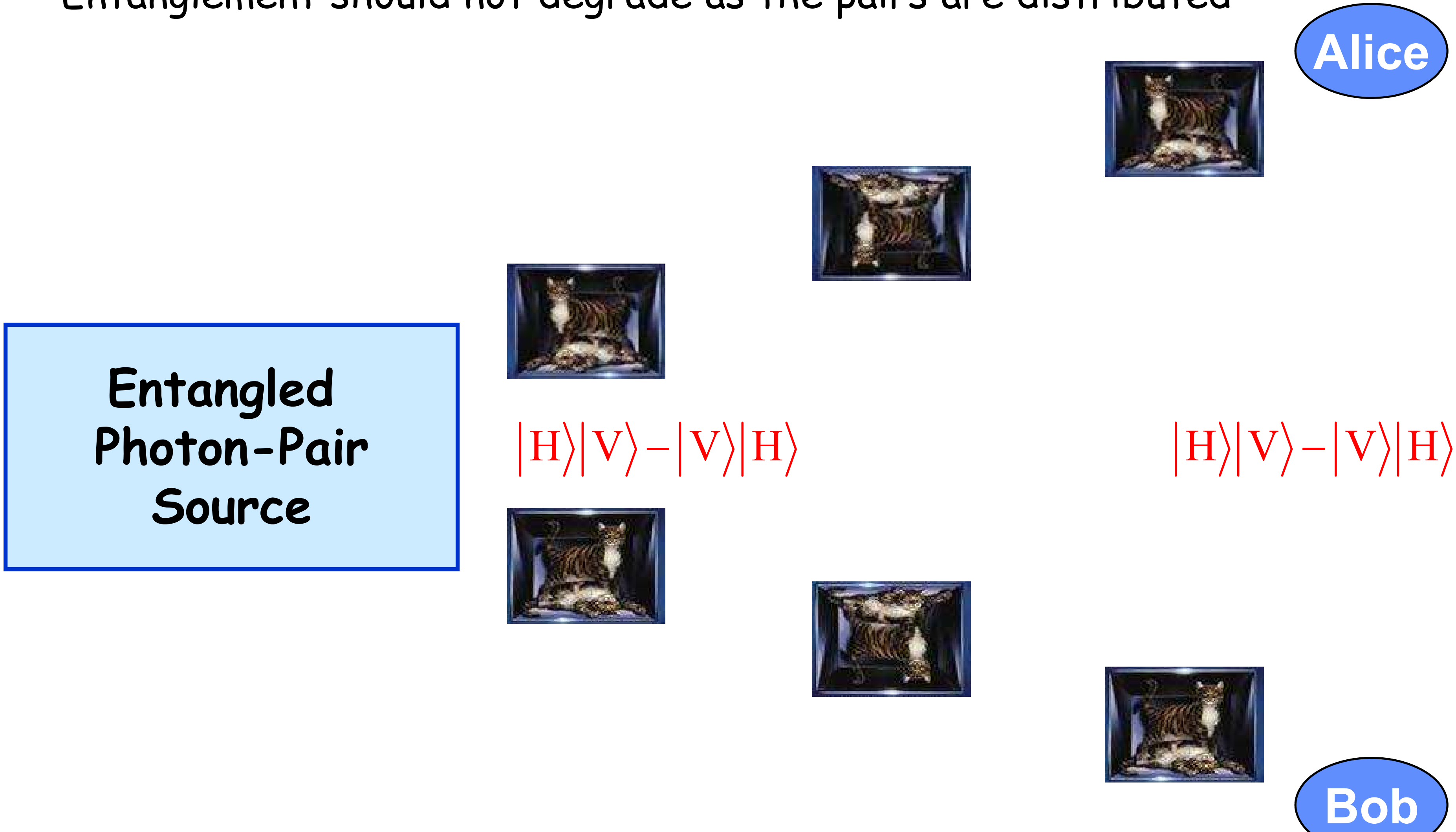
Requirements for Such Connectionless Quantum Communication

- Ubiquitous availability of entangled photon pairs
  - Efficient sources of entangled photon pairs
  - Efficient distribution of quantum entanglement
- Technologies for storage and on-demand recall of entangled photons for the users
  - Technologies for mapping entanglement from one modality to another, e.g., from photonic states to matter states
  - Or one qubit in matter states while the other on a photon
- Technologies for quantum measurements (Bell states)
  - Efficient single/correlated photon detection
  - Unconditional bell-state measurements/analysis

Photon loss is the bane of quantum communications !
And, of course, phase decoherence !!!

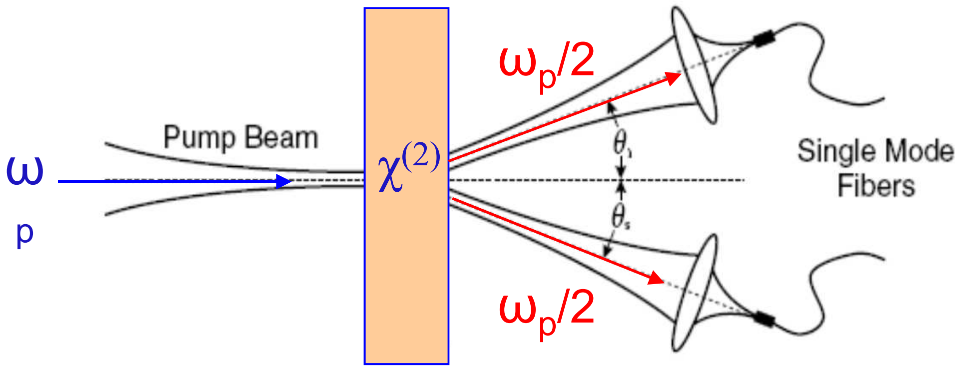
Desirable Features of an Entanglement Source

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



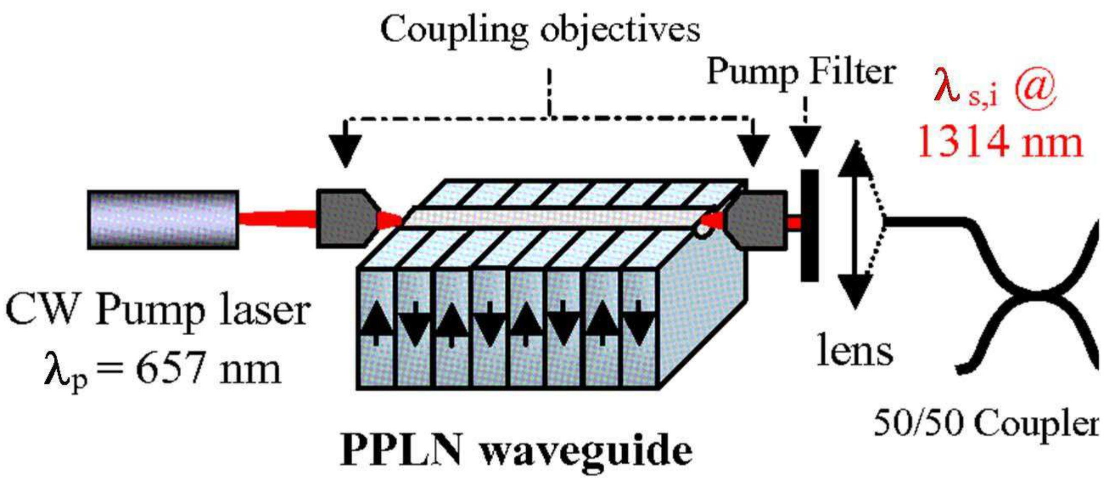
Crystal-Based Approaches

SPDC For example, S. Castelletto *et al.*, *New. J. Phys.* **6**, 87 (2004)



- Typically not in telecom band
- Spatial mode profile incompatible with single-mode fiber
- Loss of entanglement when coupled into SMF

SPDC in Waveguides S. Tanzilli *et al.*, Euro Phys. J. D **18**, 155 (2002)



- Pump still not in the telecom band
- Spatial mode profile better matched, but not perfect

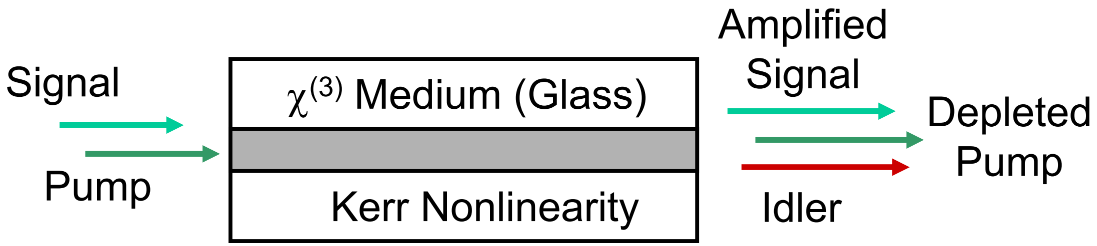
Our Motivation for using Fibers

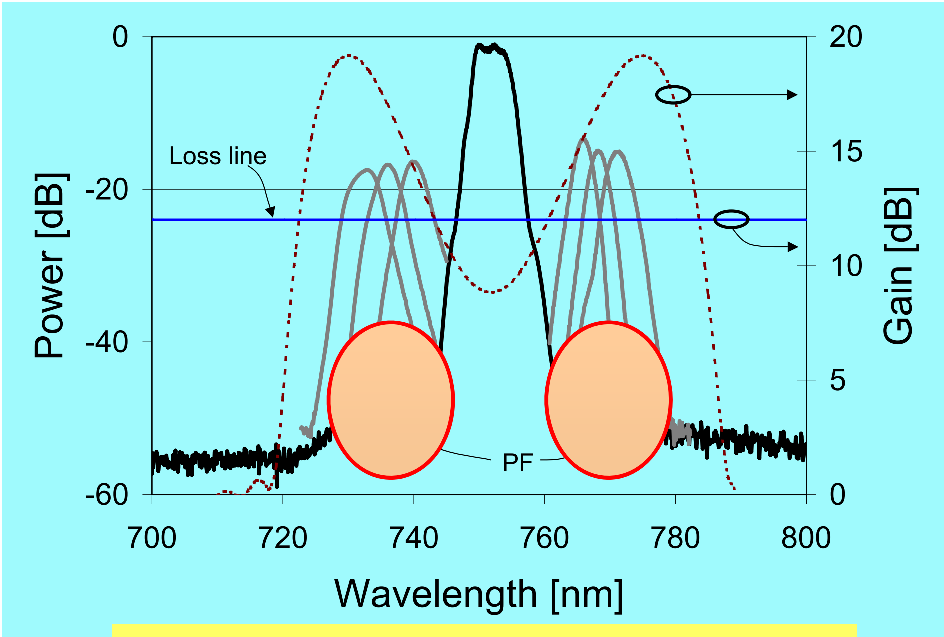
- Realistic long-distance quantum communication must integrate with existing optical-fiber networks
- Fiber offers several advantages over $\chi^{(2)}$:
  - Excellent modal purity, highly desirable for schemes requiring multiple quantum interactions
  - Possible to wavelength multiplex several entangled channels on existing fiber plant
  - Avoids coupling photons from $\chi^{(2)}$ crystals into fiber
  - Long distance operation possible, owing to high quality of commonly available optical fibers
- Side benefit: Allowing us to investigate fundamental limits of practical optical communication technology

Outline

- What is quantum communications?
- Requirements for implementing quantum communications
- Fiber-based sources of correlated / entangled photons
  - Nondegenerate polarization entangled
- Ultrafast switching of photonic entanglement
  - Ultrafast MUX / DEMUX of quantum data channels
- Conclusions and future outlook

Four-Wave Mixing and Parametric Fluorescence in Optical Fiber



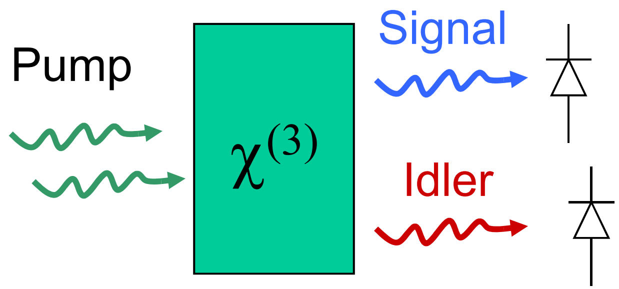


Serkland et al. OL ***23****, 795 (1998) in DSF*
Sharping et al., OL ***27****, 1675 (2002) in MF*

Strong parametric fluorescence is easily observed at moderate pump power

At the Quantum Level:

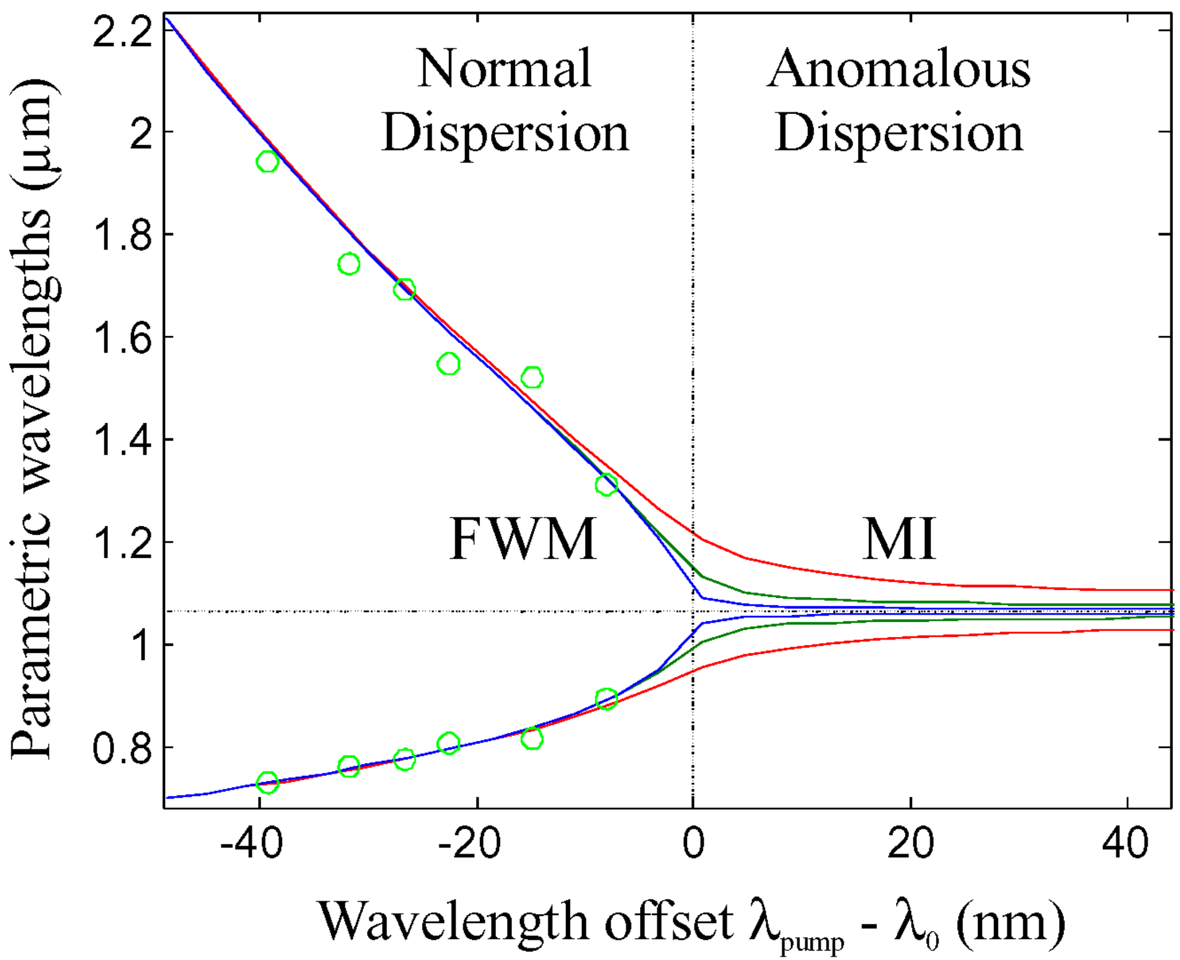
- FWM is nondegenerate optical parametric amplification (OPA), as in $\chi^{(2)}$ crystals
- Signal and idler photons are created in pairs
- *They exhibit entanglement properties similar to signal and idler photons created in $\chi^{(2)}$ parametric down-conversion*

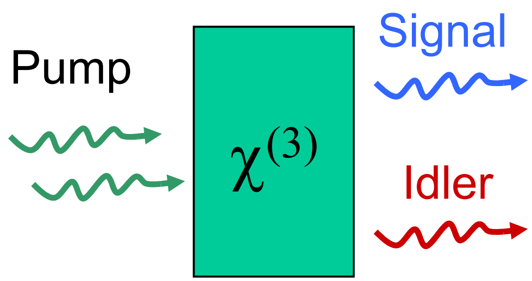


M. Fiorentino *et al.*, IEEE PTL **14**, 983 (2002)
X. Li *et al.*, PRL **94**, 053601 (2005)

Migdall *et al.* & Rarity *et al.* (2005-2007)

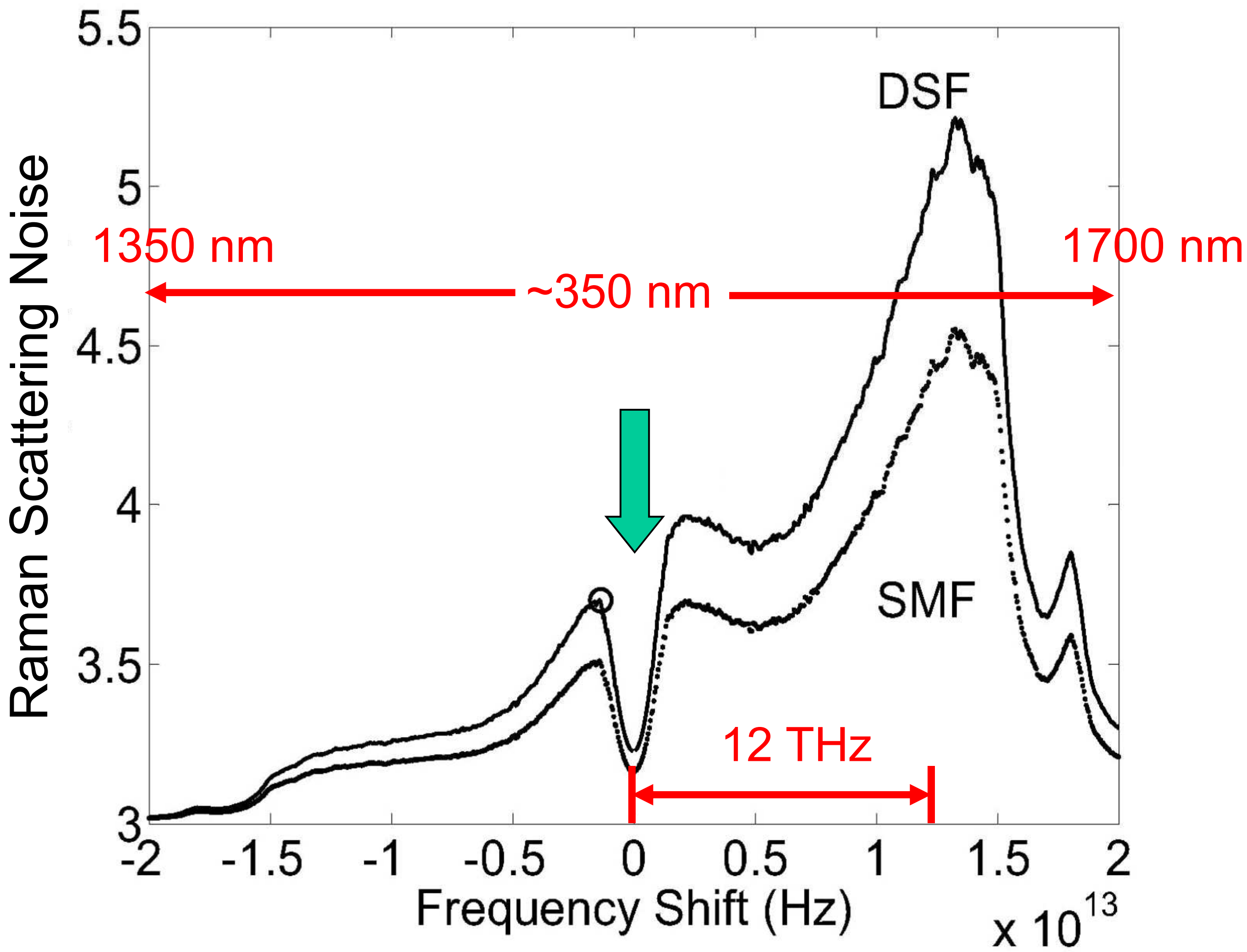
Phase-Matching Considerations





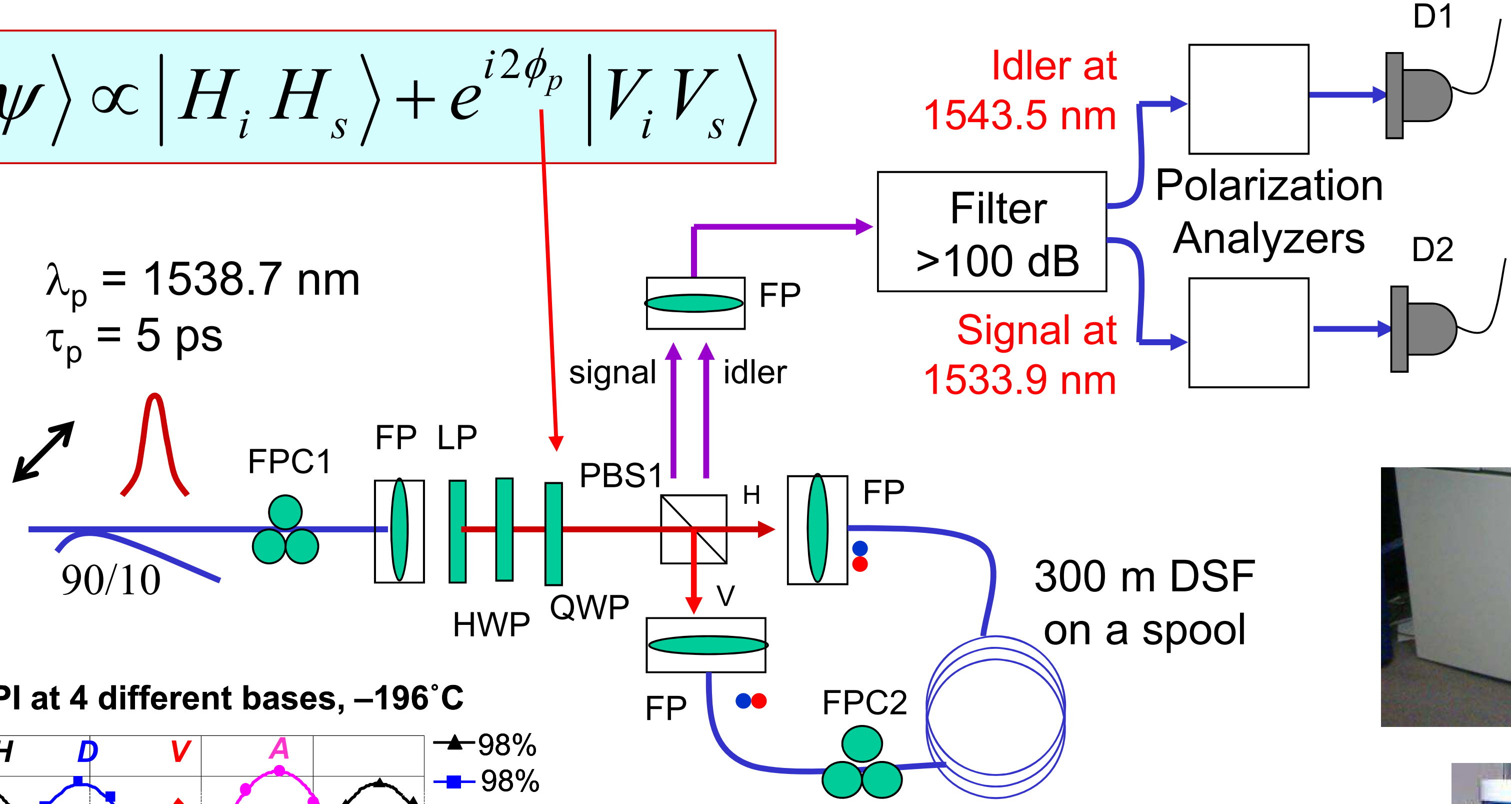
Migdall *et al.* & Rarity *et al.* (2005-2007)

Our Solution: Cool the Fiber

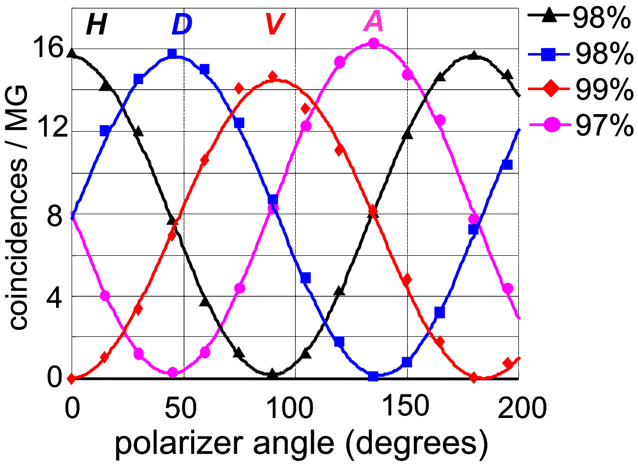


Fiber-Based Source of Polarization-Entangled Photon Pairs

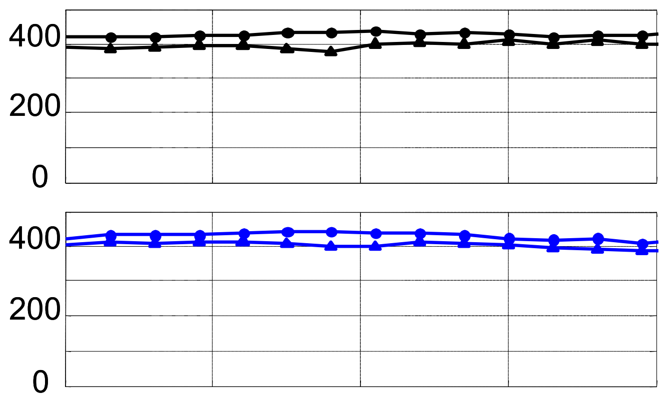
$$|\psi\rangle \propto |H_i H_s\rangle + e^{i2\phi_p}|V_i V_s\rangle$$



TPI at 4 different bases, –196˚C

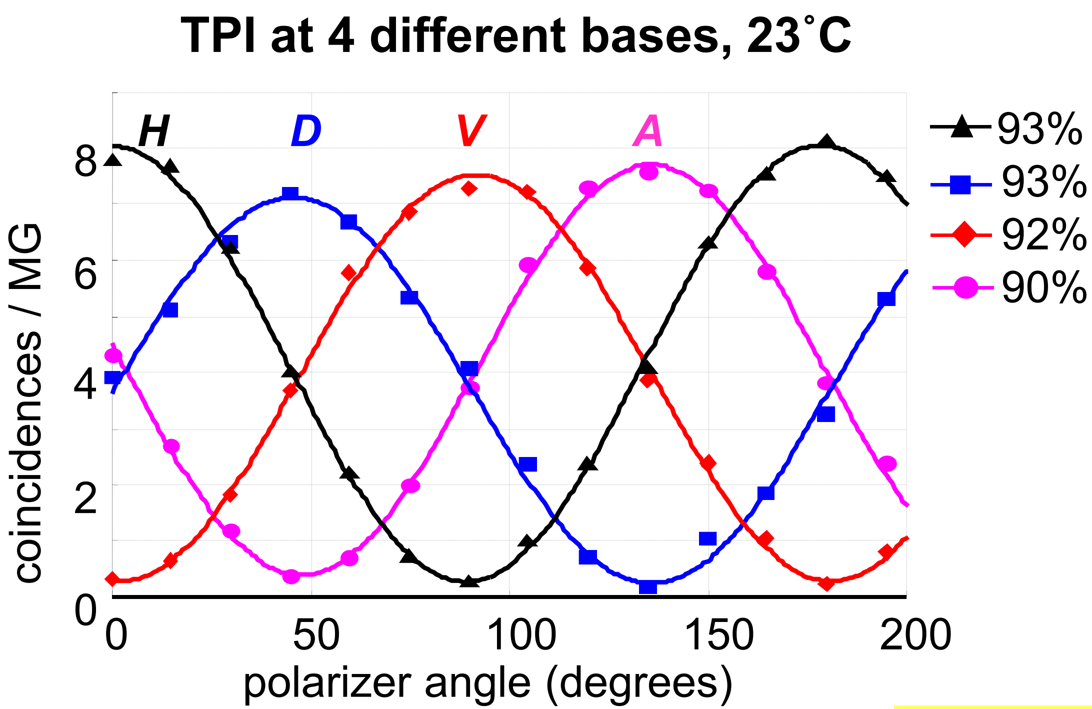


Singles Counts



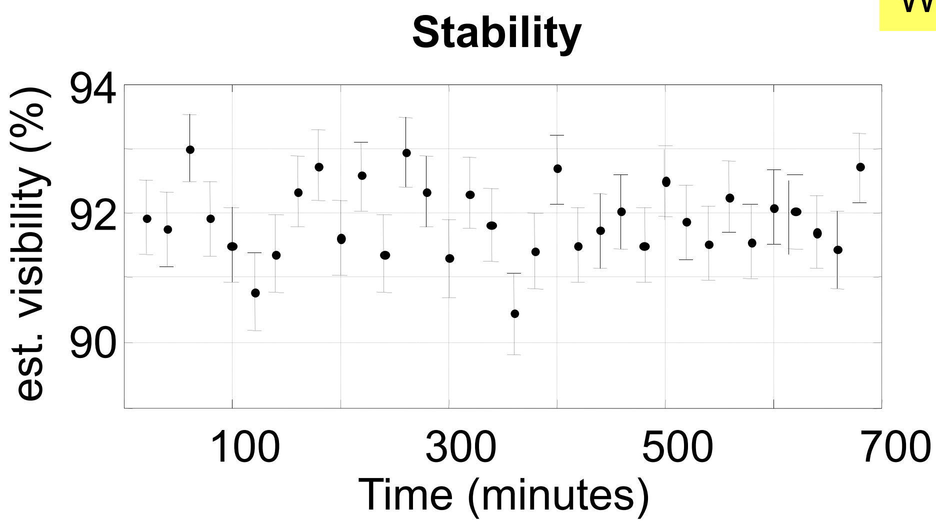
Wang & Kanter, IEEE JSTQE **15**, 1733 (2009)

Room Temperature and Stability Data

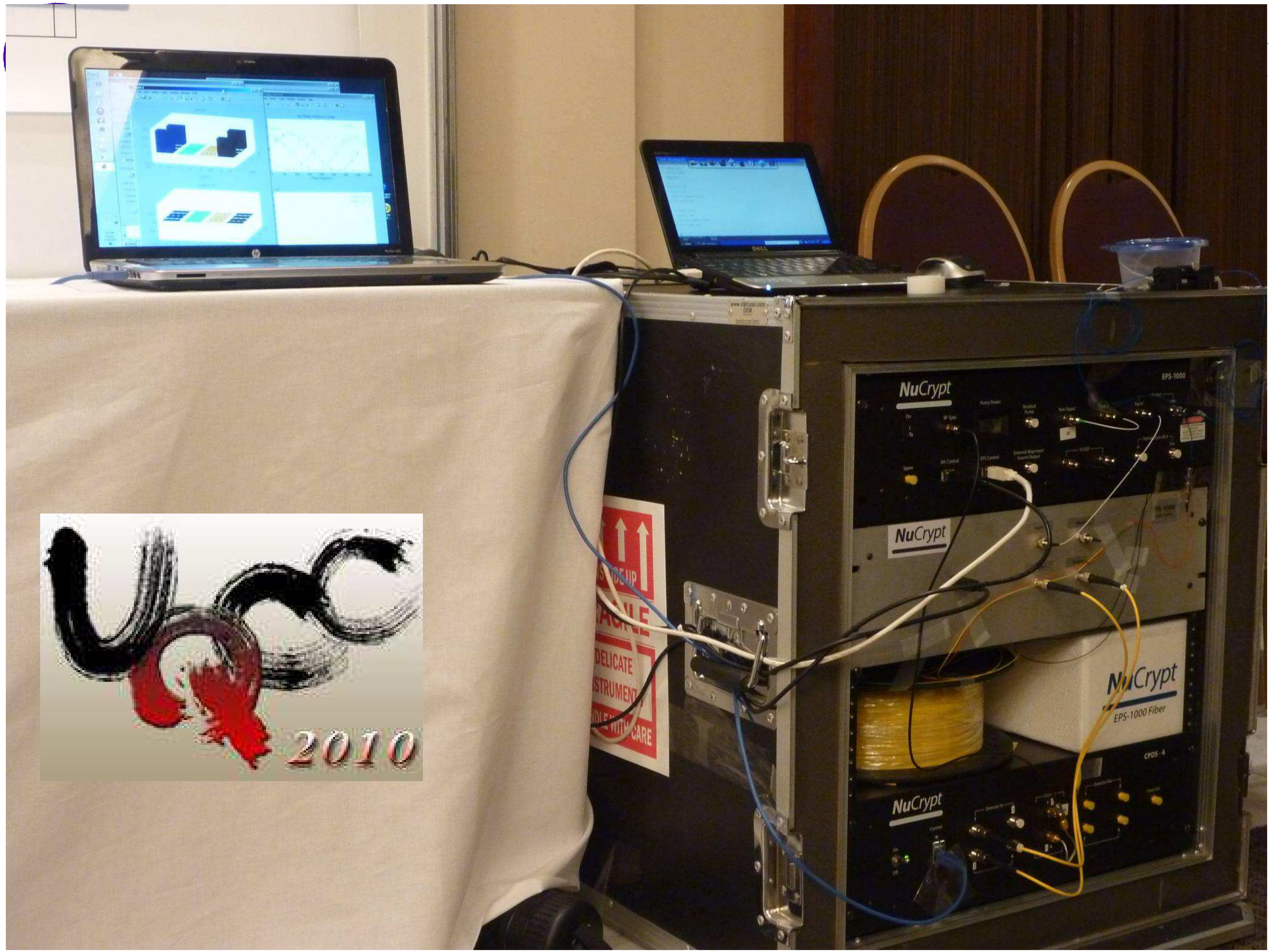


- **Good but somewhat reduced performance at room temperature**
- **Note, however, that this level of performance is still very good; TPI > 0.71 indicates violation of Bell's inequalities**

Wang & Kanter, IEEE JSTQE **15**, 1733–1740 (2009)



- **Sit at fringe minimum with no adjustments to source**
- **Very stable output**


NuCrypt
EPS-1000
NuCrypt
NuCrypt
EPS-1000 Fiber
NuCrypt
2010

Entangled Photon Source Specification Sheet

http://nucrypt.net/entangled-photon-source.html

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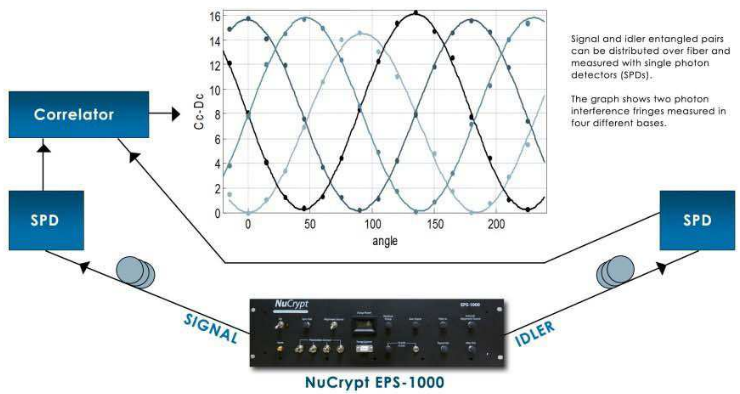
NuCrypt

Entangled Photons Source (EPS-1000)

Product Overview — *2009*

NuCrypt has developed a fiber-coupled source of entangled photons which is remarkably easy to use. The source is inherently compatible with fiber optics, has excellent modal purity, and high spectral brightness. NuCrypt's patent pending architecture for the entangled photons source leads to a stable output and allows for an "alignment" mode of operation to make it easy for the users to align their measurement basis (polarization analyzers) to a desired orientation. The rack-mountable source is simple enough for non-experts in the field to use and thereby greatly expands the potential for applications development. The pair-emission rate is computer controlled. Upon request, the nonlinear fiber can be mounted outside the source so it can be cooled by the user to reduce Raman scattering, thereby improving the source's performance.



Signal and idler entangled pairs can be distributed over fiber and measured with single photon detectors (SPDs).

The graph shows two photon interference fringes measured in four different bases.

- Distribution of polarization entangled photons over fiber
- Use in quantum cryptography, quantum imaging, or quantum metrology applications
- Stable fiber optical output with high spectral purity and brightness

1840 Oak Avenue, Suite 212-S, Evanston, IL 60201-3697; Tel.: (847) 733-8750

NuCrypt

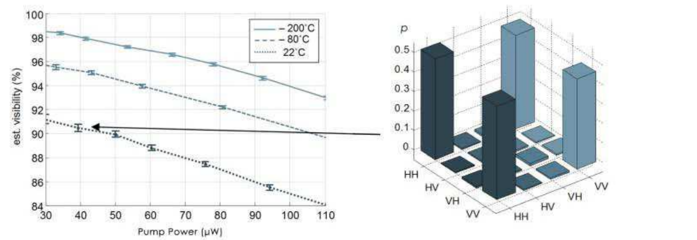
Entangled Photons Source (EPS-1000)

Product Specifications — *2009*

Attribute	Value	Units	Comments
Pulse Rate	50	MHZ	
Signal Wavelength	1550.1	nm	Other Values on the ITU grid are available
Idler Wavelength	1558.1	nm	Other Values on the ITU grid are available
Signal photon 3-dB bandwidth	1.0	nm	Transform limited pulse
Idler photon 3-dB bandwidth	1.0	nm	Transform limited pulse
Signal/Idler photon duration	~5	ps	
Pair-emission probability (p)	0.0001 to >0.005	per pulse	User settable, inferred at fiber tips after filtering*
TPI visibility (300K)	{90, 85}	%	{p ~ 0.0003, p ~ 0.001}
TPI visibility (77K)	{97, 93}	%	{p ~ 0.0005, p ~ 0.002}
Form factor			Standard 5U 19" rack mountable box

TPI = Two-photon interference
* Example calculation of expected measured coincidence-count (CC) rate.
Assume: polarization-analyzer tranmittance = 0.7, single photon gate rate of 5 MHz with 25% detection efficiency, and p ~ 0.0005:
CC = 5 x 10^6 * 0.0005 * $(0.7 * 0.25)^2$ = 77/s [photon-pair emission rate at fiber tips = 25,000/s at 50 MHz pump-pulse rate]

- Electrical and optical clock signals at the repetition rate for synchronizing detectors
- Computer controllable two-photon generation rate
- Built-in polarized alignment signal for easy alignment of measurement analyzers



Expected TPI visibility as a function of computer-controlled pump power at various fiber temperatures. Two-photon generation rate improves quadratically with pump power, but due to multiphoton effects the quality of entanglement degrades, lowering the TPI visibility.

Corresponding tomography at 40μW of power with the fiber at room temperature.

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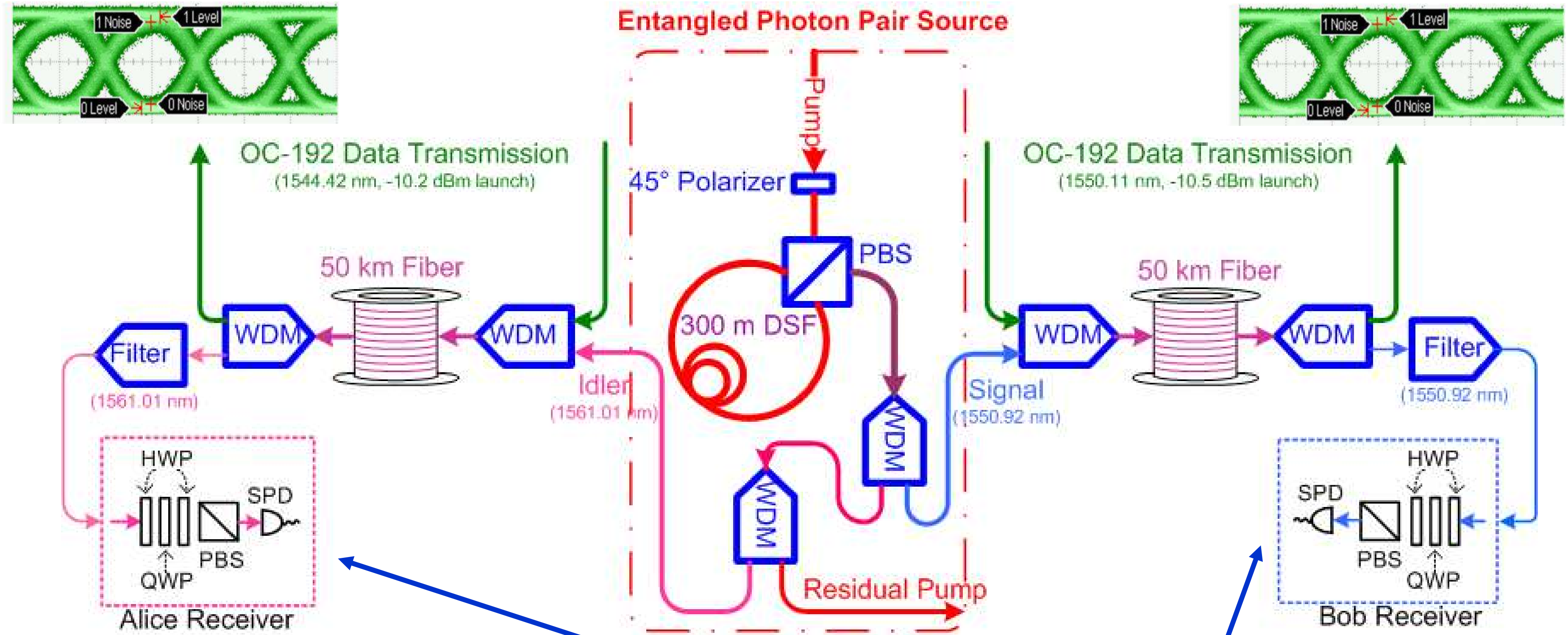
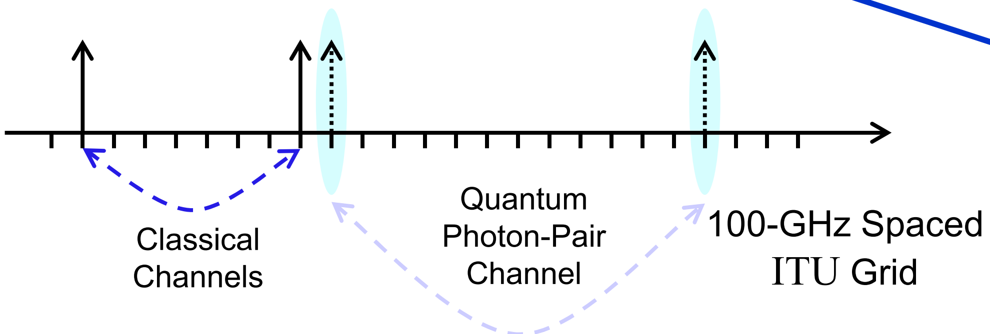
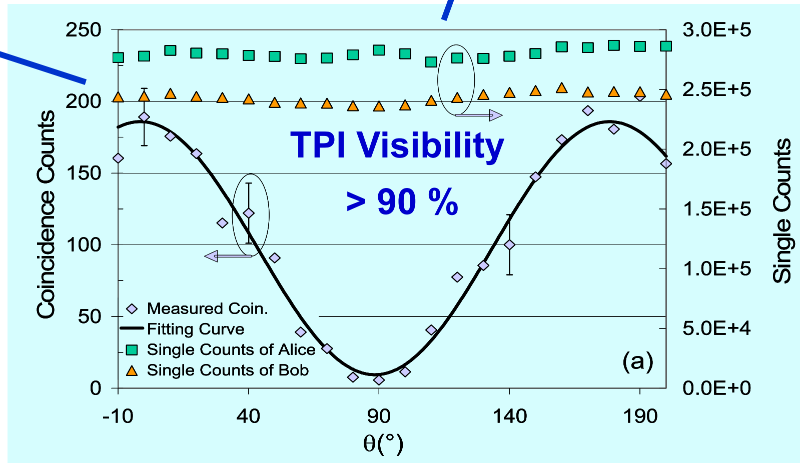
Sales are subject to NuCrypt's terms and conditions. Specifications subject to change without notice.

Entanglement Distribution in WDM Environment



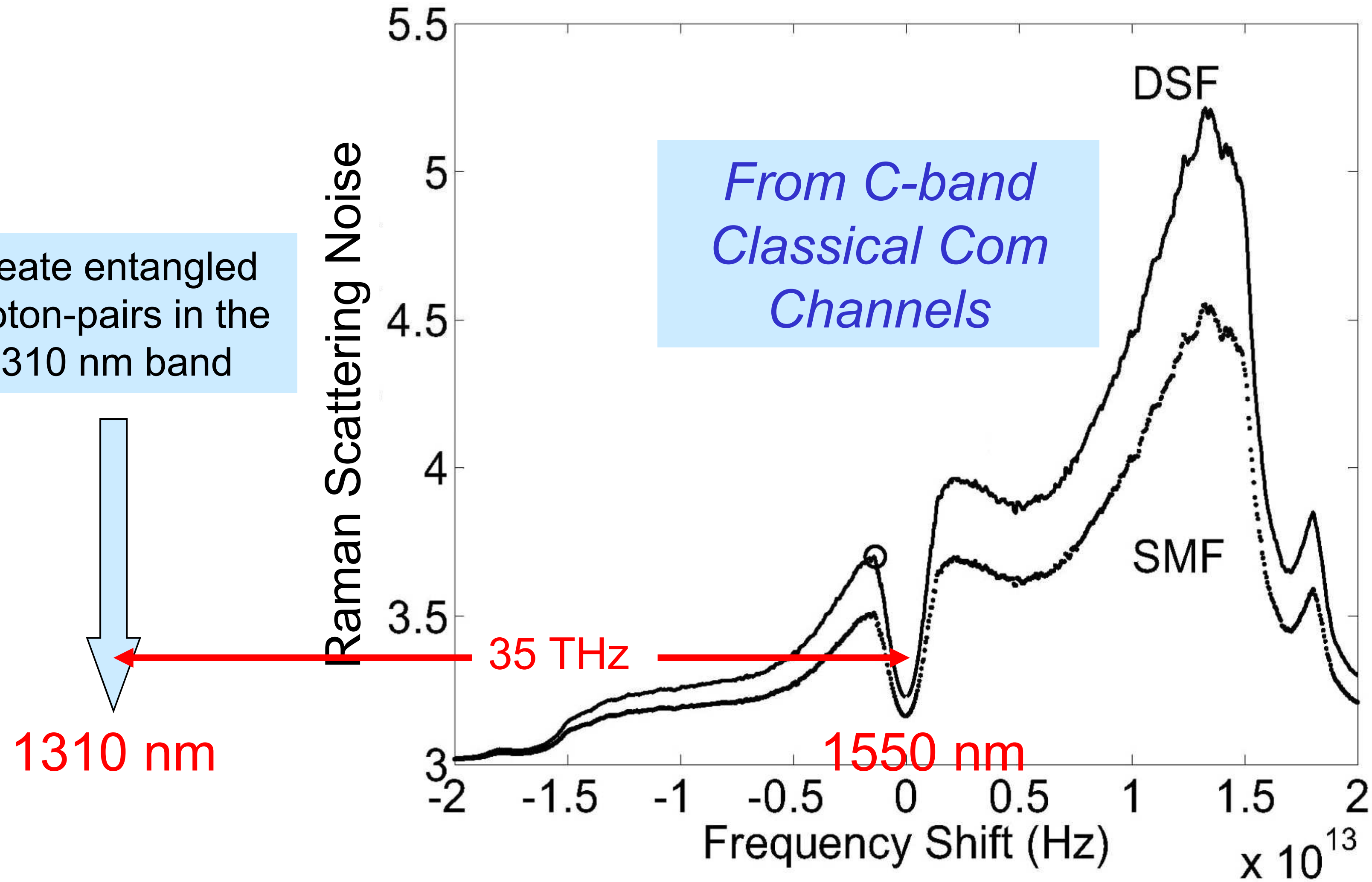




Liang *et al.*, *OFC 2006 postdeadline paper PDP35*

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)

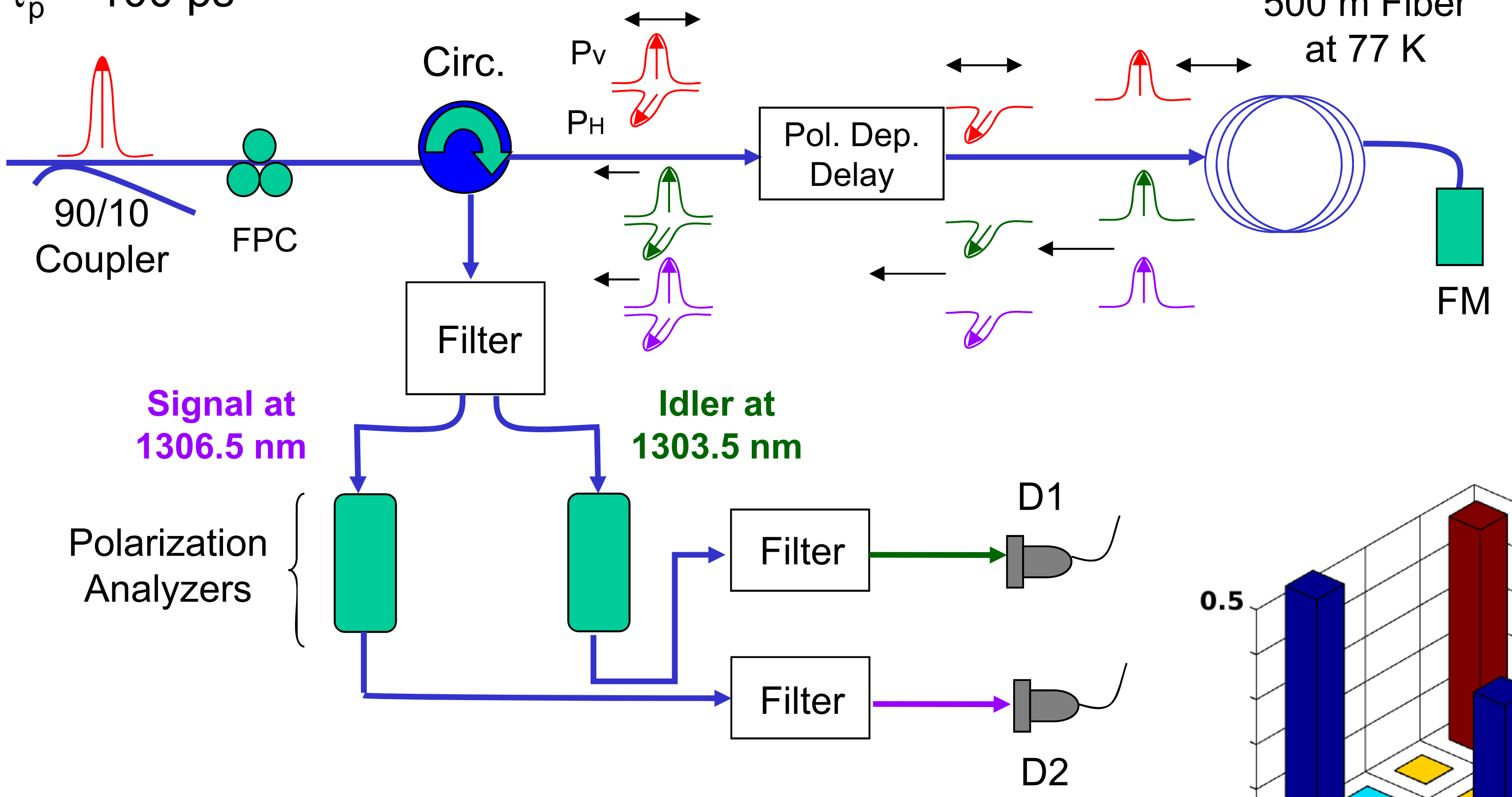
O-band Entanglement Generation

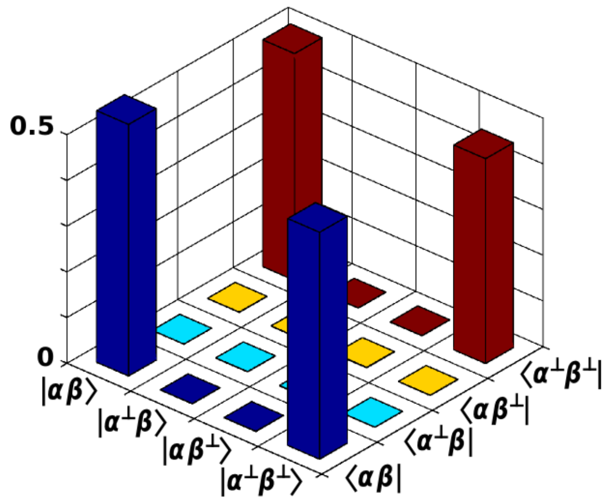
Pulses carved from a CW laser at 50 MHz

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

λ_p = 1305 nm

τ_p = 100 ps

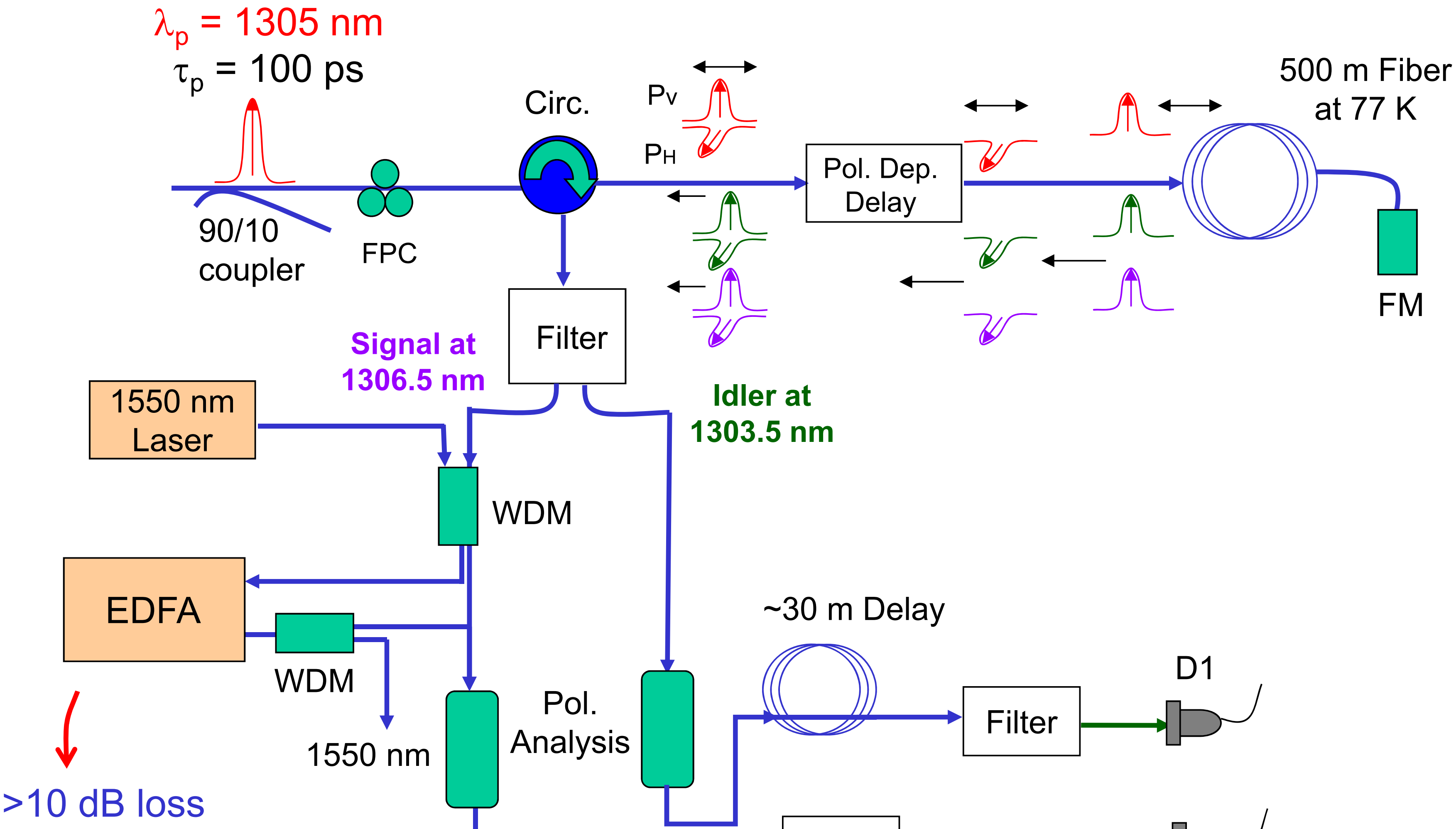




- 1.5 nm detuning from pump
  - Reduced SRS
- Potential for 10 GHz Operation

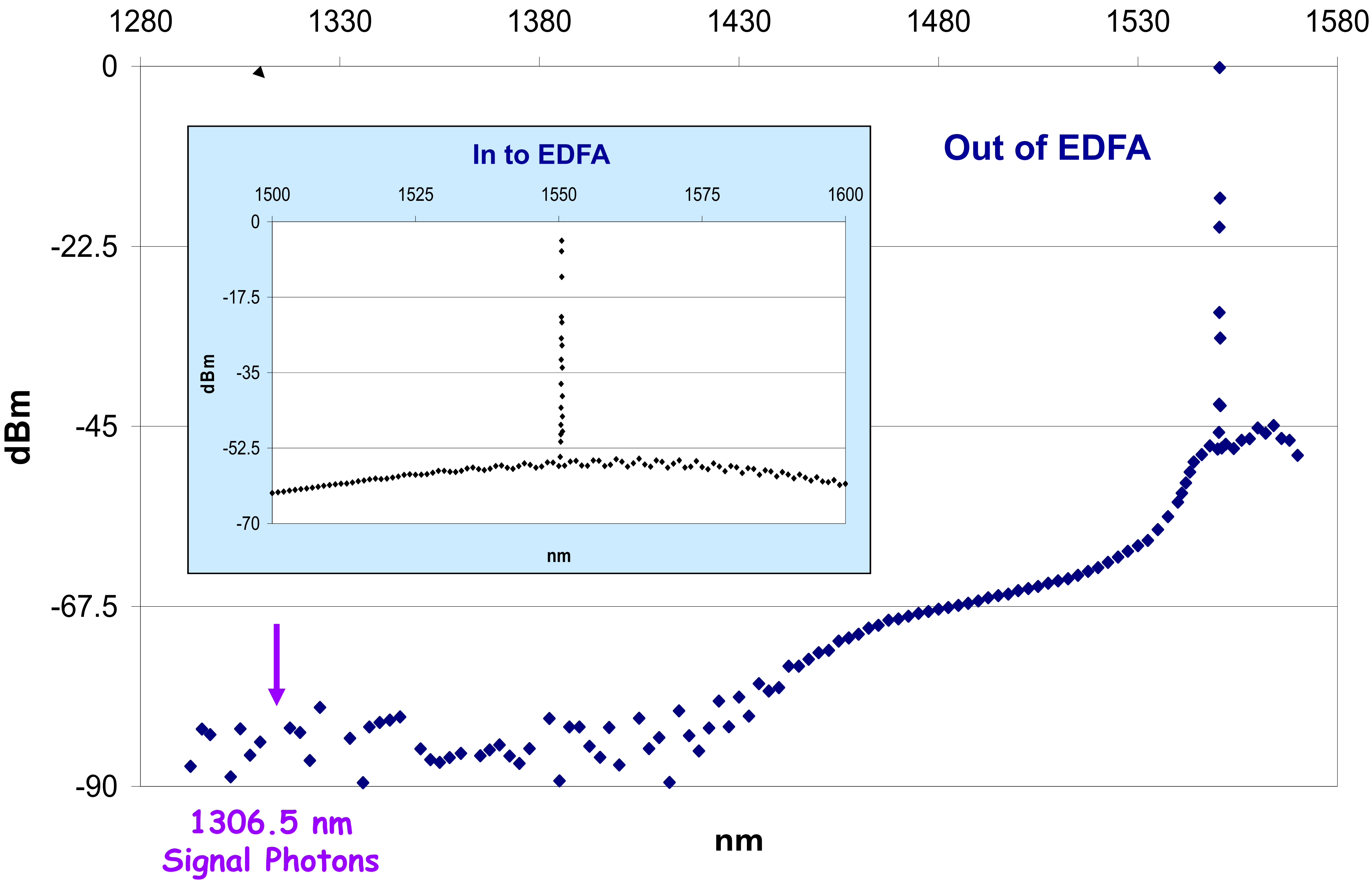
F = 99.6 ± 0.15%

Co-existence of O-band Entanglement with C-band (1550 nm) Hardware



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

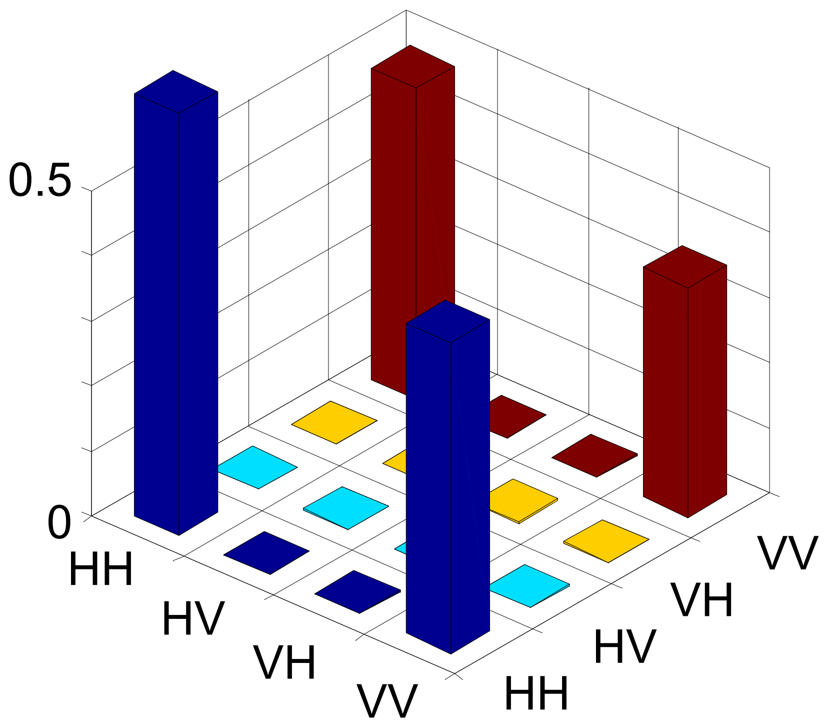
In / Out Spectra of the Classical 1550 nm Channel



Entanglement Before and After EDFA

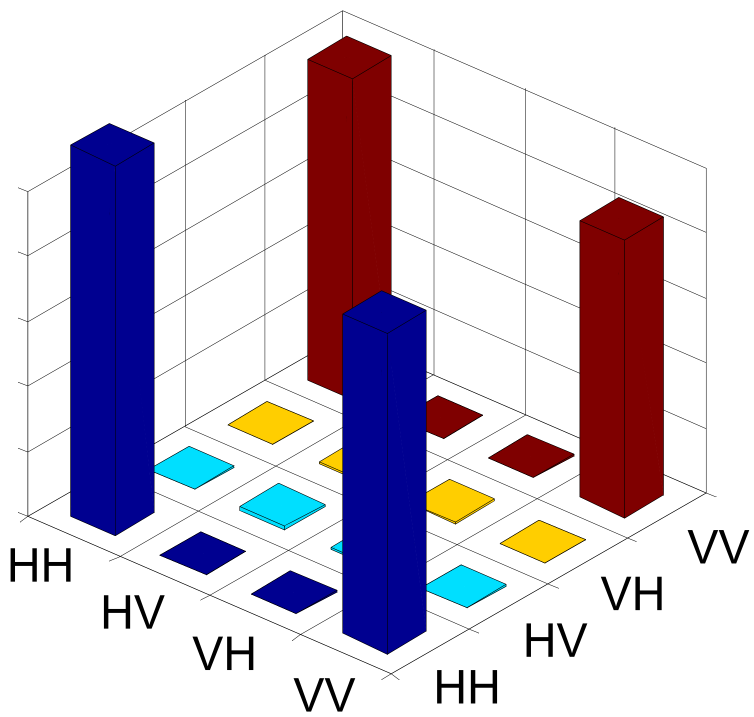
Hall, Altepeter, & PK, OpEx **17**, 14558 (2009)

Before EDFA



Fidelity > 97%

After EDFA



No discernable change in fidelity

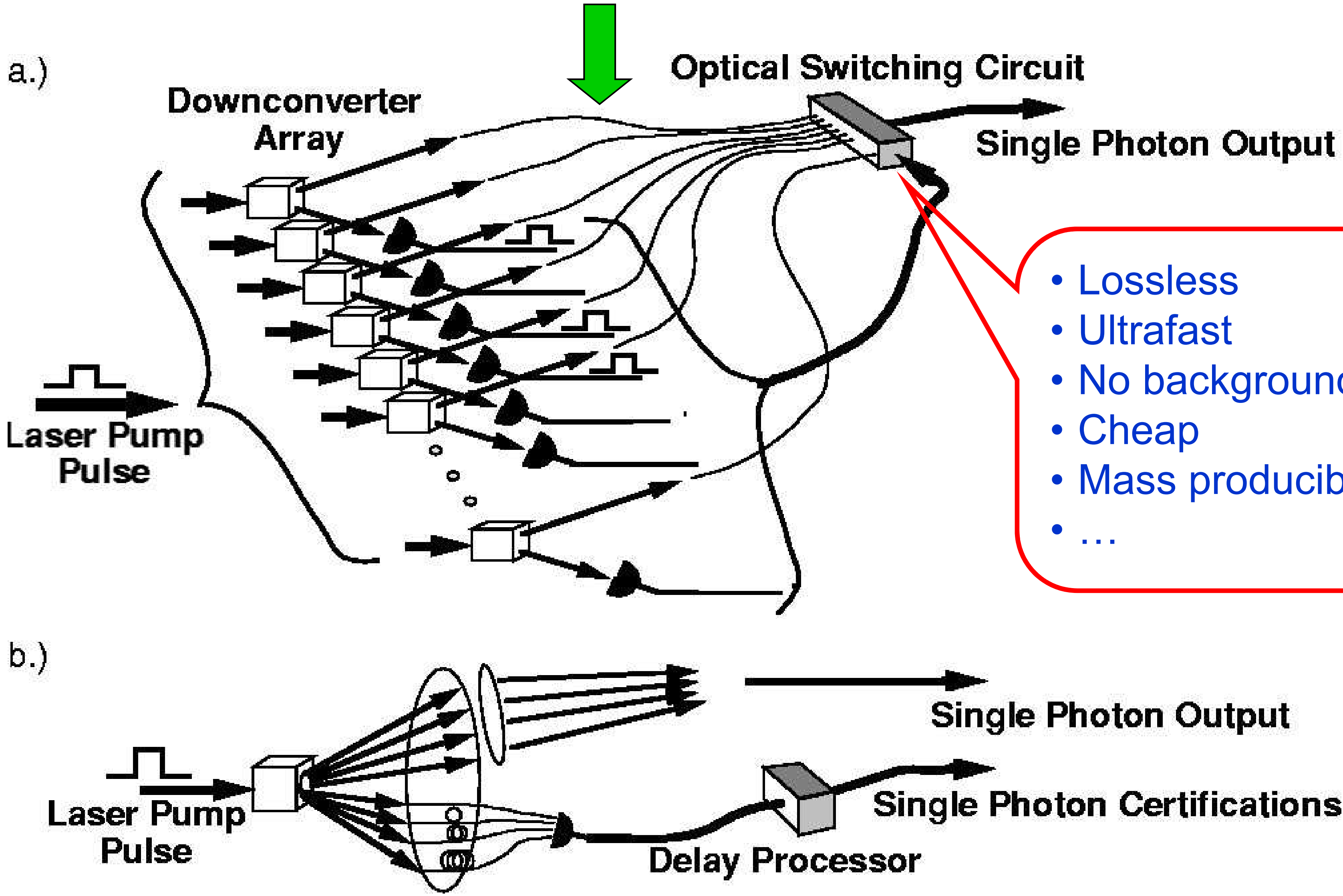
Source Summary and Scaling to 10 GHz

- Pump Pulse Characteristics
  - Rep rate = 50 MHz
  - Typical pulse width 5 ps (about 1 nm transform limited bandwidth)
  - Avg. photon # / pulse: 10^7–10^8 for pair production prob. 1–5% in ~100 m DSF
  - Typical average power ~ 0.3 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 ~ 60 mW
  - Easily achievable with mode-locked fiber or semiconductor lasers
- However, single-photon detection is still a bottleneck for developing quantum communication applications in the telecom band
  - InGaAs-based APDs can be gated only up to 10–100 MHz (long dead time)
  - Faster superconducting detectors on the horizon, but still not available
- Optical demultiplexing is a potential near-term solution

Outline

- What is quantum communications?
- Requirements for implementing quantum communications
- Fiber-based sources of correlated / entangled photons
  - Nondegenerate polarization entangled
- Ultrafast switching of photonic entanglement
  - Ultrafast MUX / DEMUX of quantum data channels
- Conclusions and future outlook

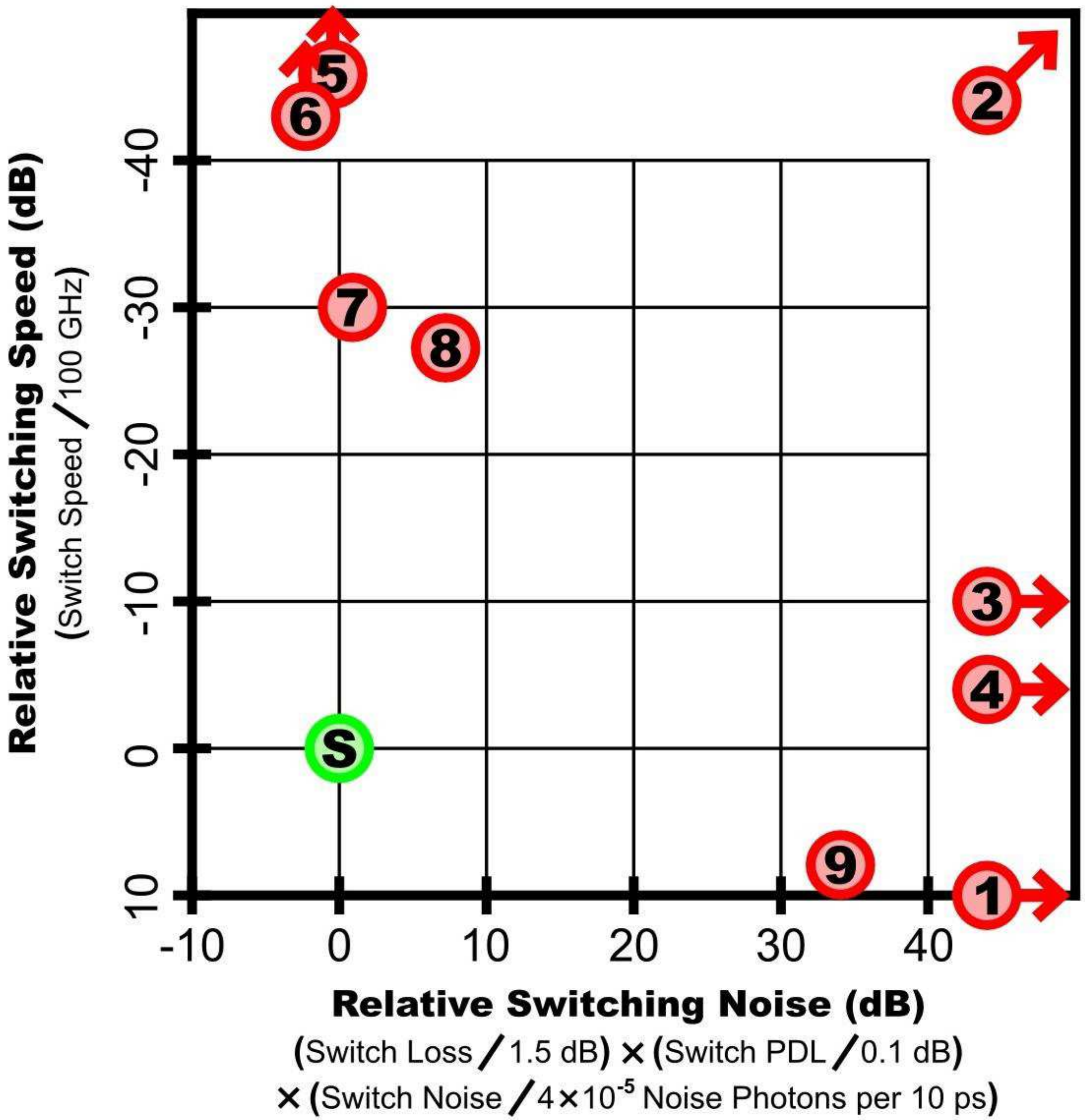
Another Motivation



- Lossless
- Ultrafast
- No background
- Cheap
- Mass producible
- …

Fig. 1: Migdall, Branning, and Castelletto, Phys. Rev. A **66**, 053805 (2002)

Relative Device Performance when Switching Polarization Entanglement

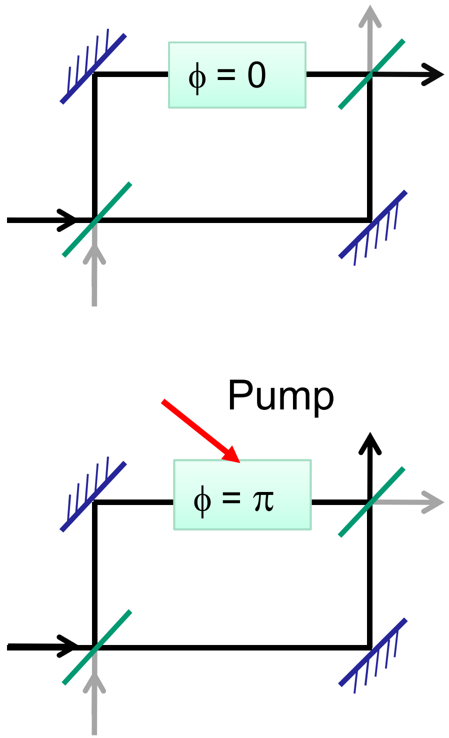


1. Polarization Based
2. Waveguide, Thermal
3. Waveguide, Resonator
4. EOM, 1x2 Modulator
5. Sagnac Effect
6. MEMs
7. EOM, 1x2 Switch
8. Acousto-Optic Modulator
9. Traditional NOLM

S. Our Switch

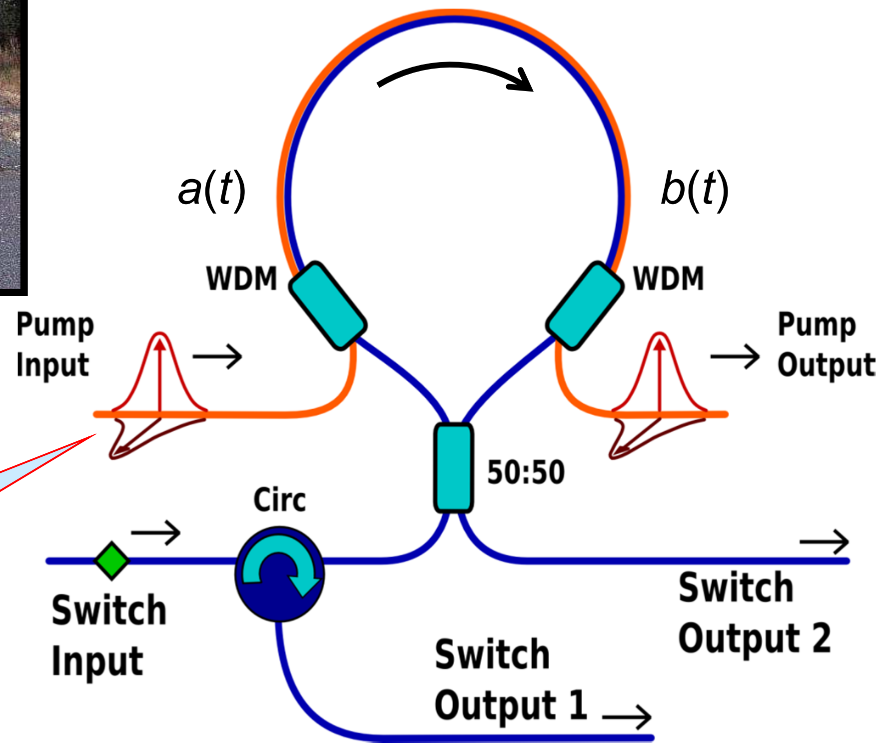
Hall, Altepeter, & PK, NJP **13**, 105004 (2011)

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



Unitary evolution in absence of Raman

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

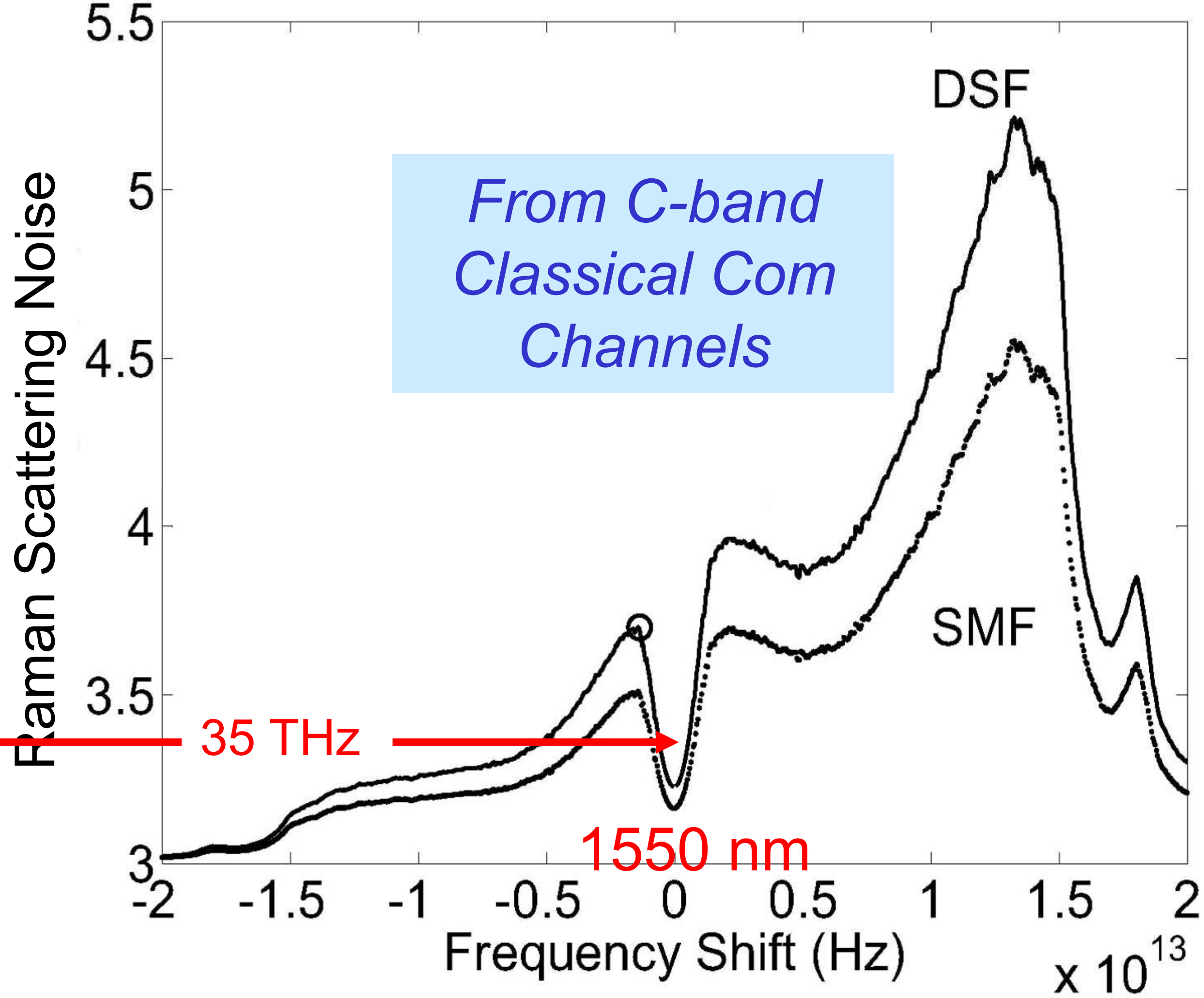


Two-Color Pump Pulses in the C-band for Polarization Independent Switching

Towards Applications in Embedded Fiber Telecom Infrastructure

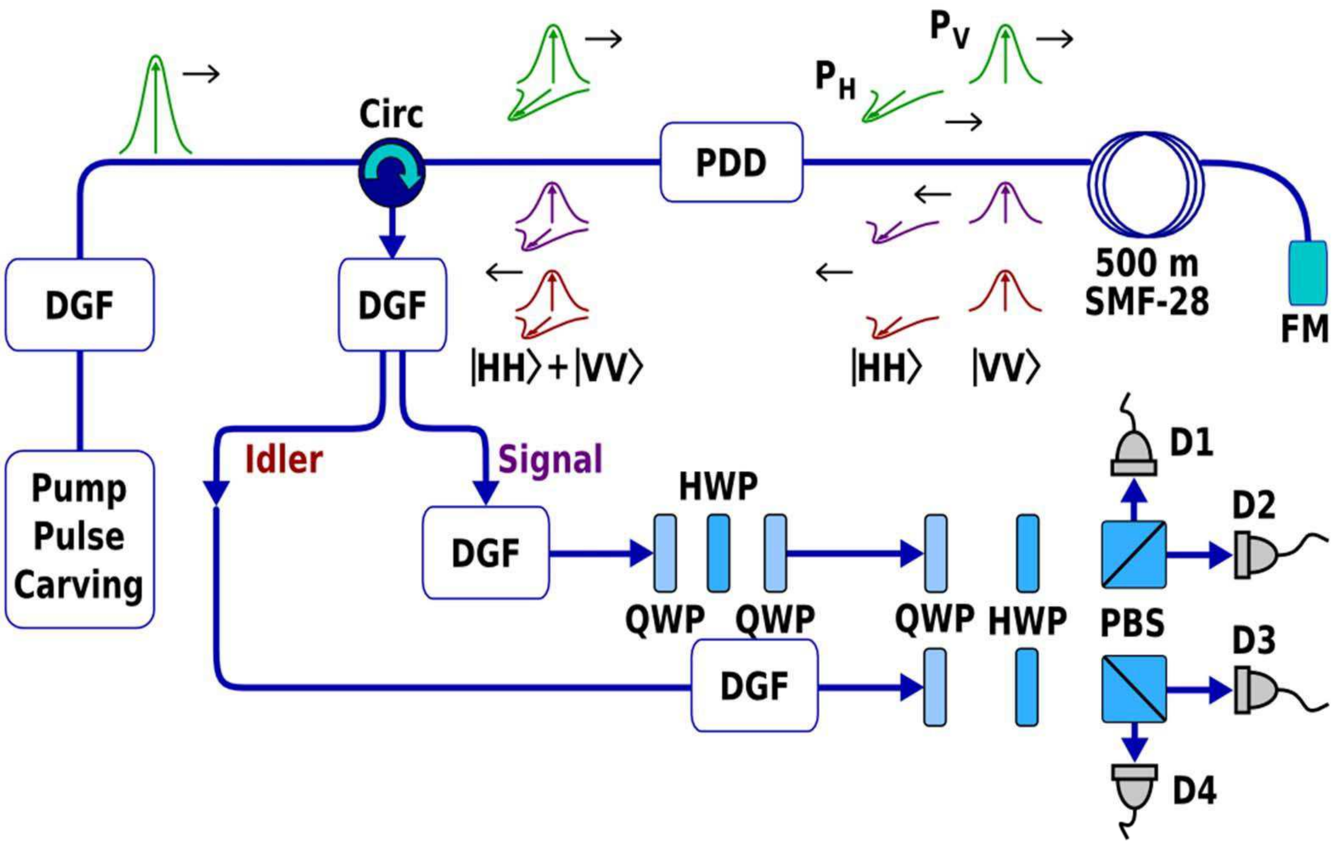
Create entangled photon-pairs in the 1310 nm band

1310 nm



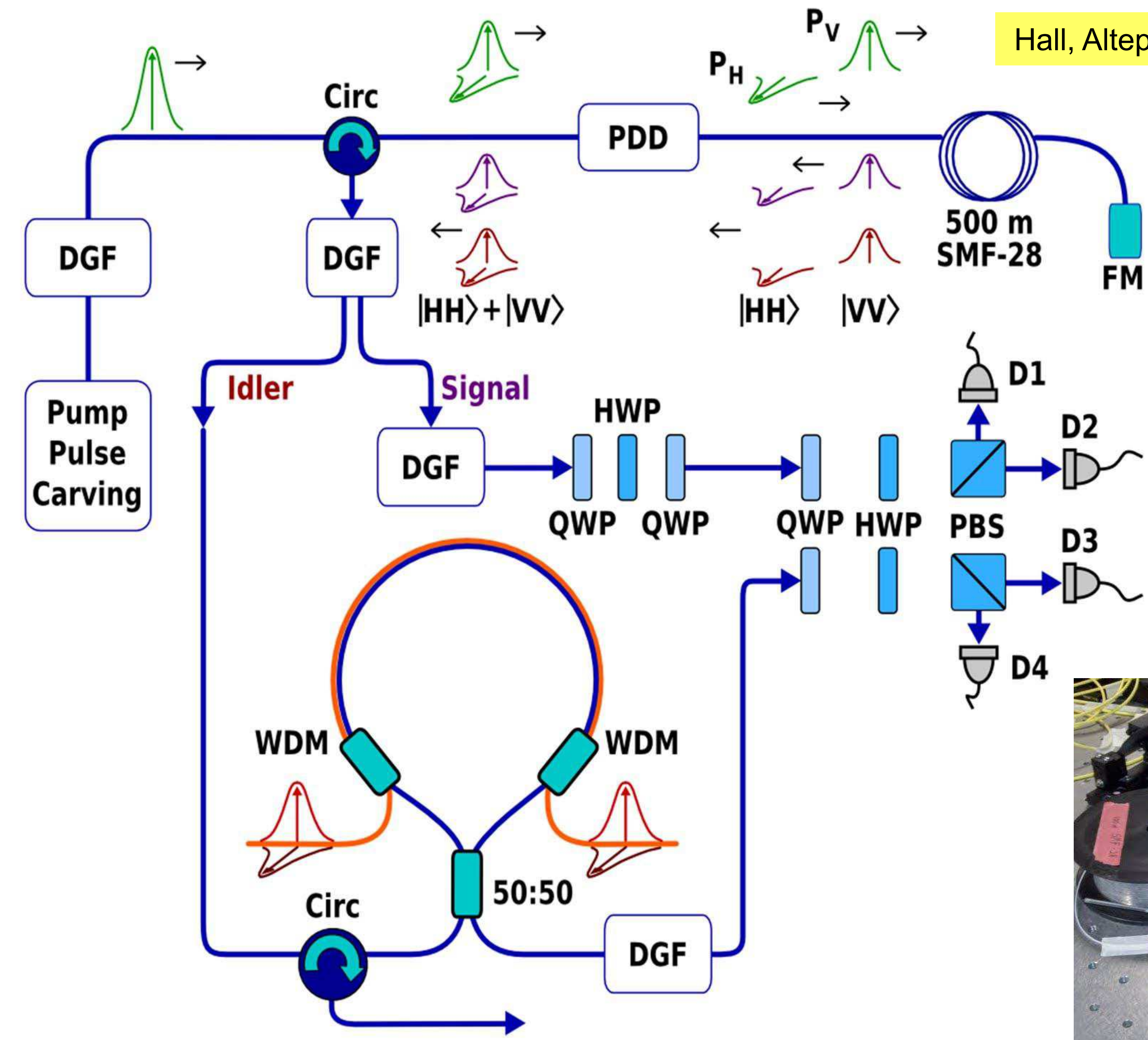
Nweke *et al.*, Appl. Phys. Lett. **87**, 174103 (2005)

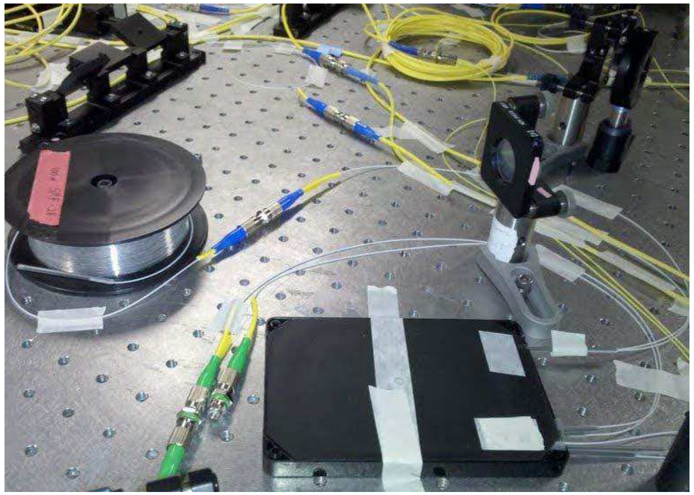
Switch Location for Quantum Testing



Switch Location for Quantum Testing

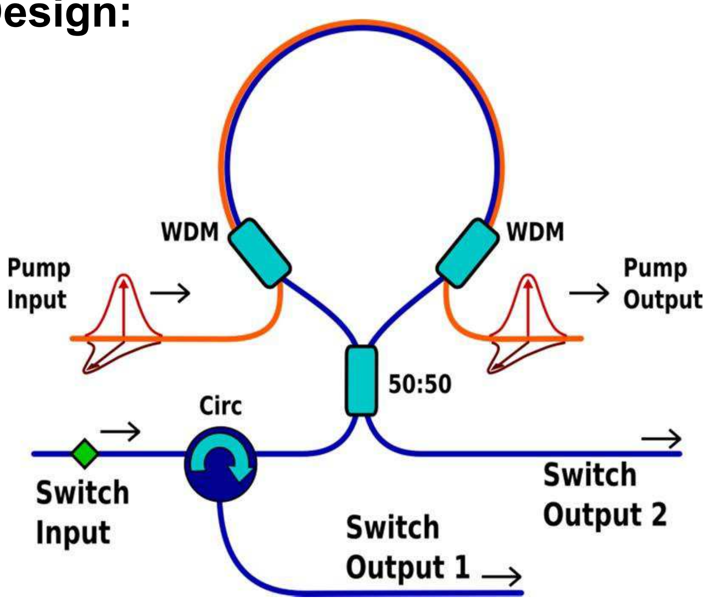
Hall, Altepeter, & PK, NJP **13**, 105004 (2011)



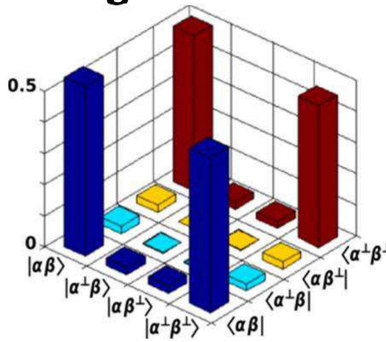


Ultrafast Switching of Photonic Entanglement

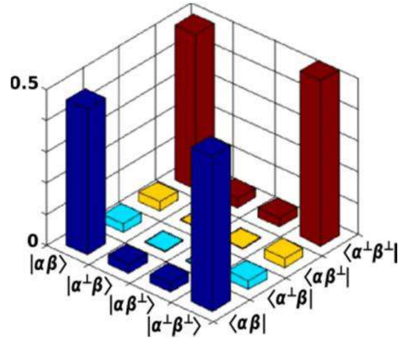
Design:



Entangled State Fidelity:



Passively Switched
F = 99.6%

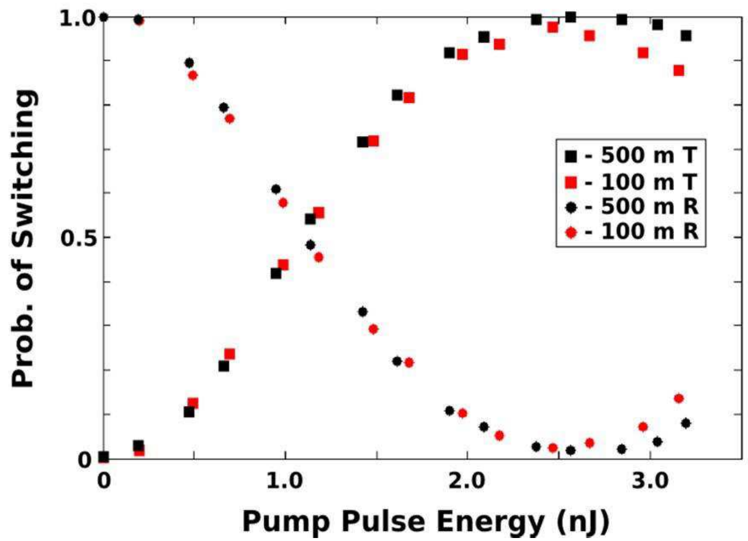


Actively Switched
F = 99.4%

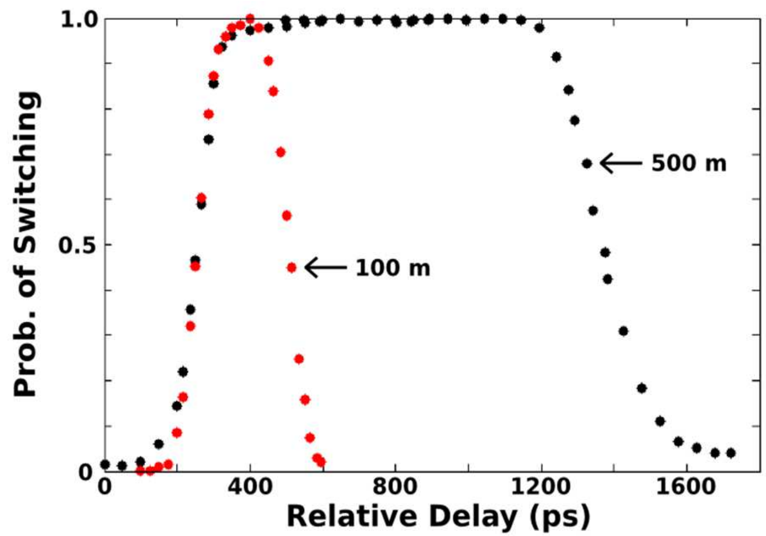
Loss:

Switch	0.9 dB
Circulator	0.4 dB

Switching Contrast: 200-to-1



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



Quantum Theory of Kerr Switching

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

Drummond
Boivin, Kaertner, Haus

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

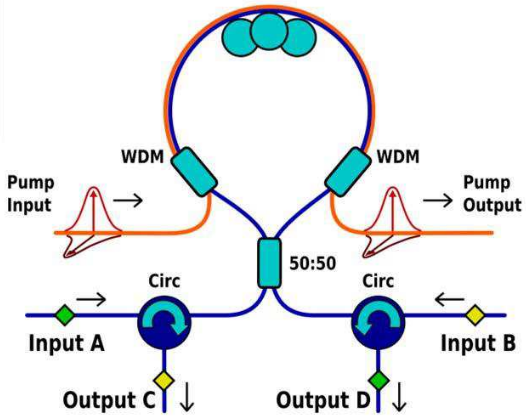
Linear loss — Coherent transformation — Ramon noise — Other quantum noise

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

Huang & Kumar, NJP, to be submitted.

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

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



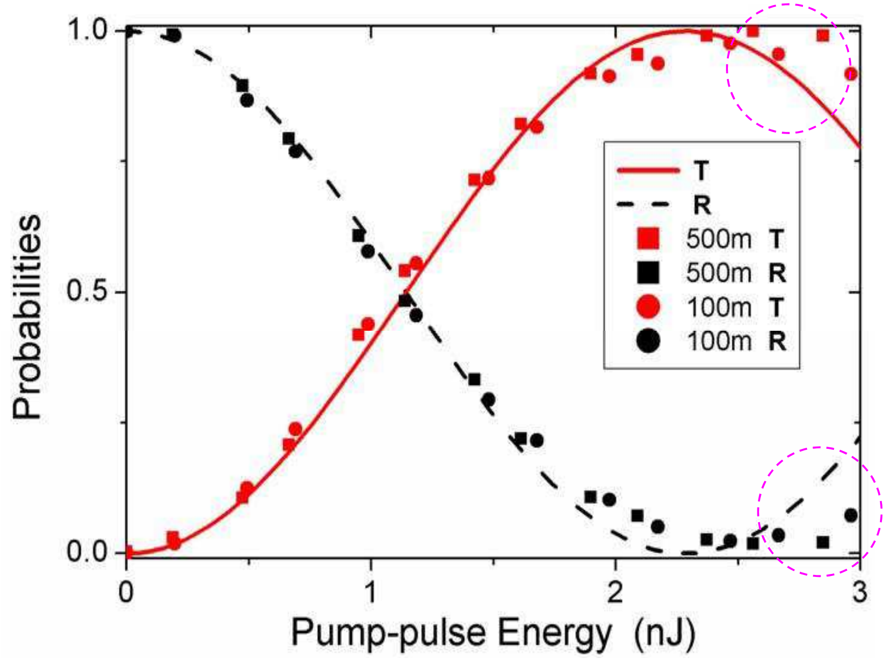
Experiment versus Theory

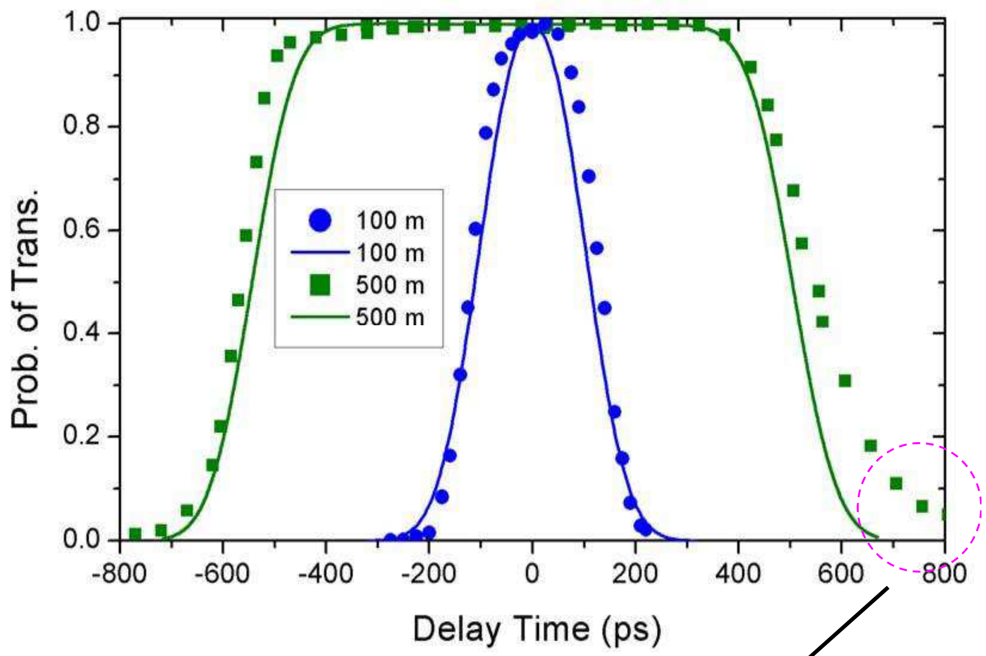
CPCC

-- No fitting parameter is used

Huang & Kumar, NJP, to be submitted.

Disagreement is likely due to nonlinear loss of the pump (currently not in model)





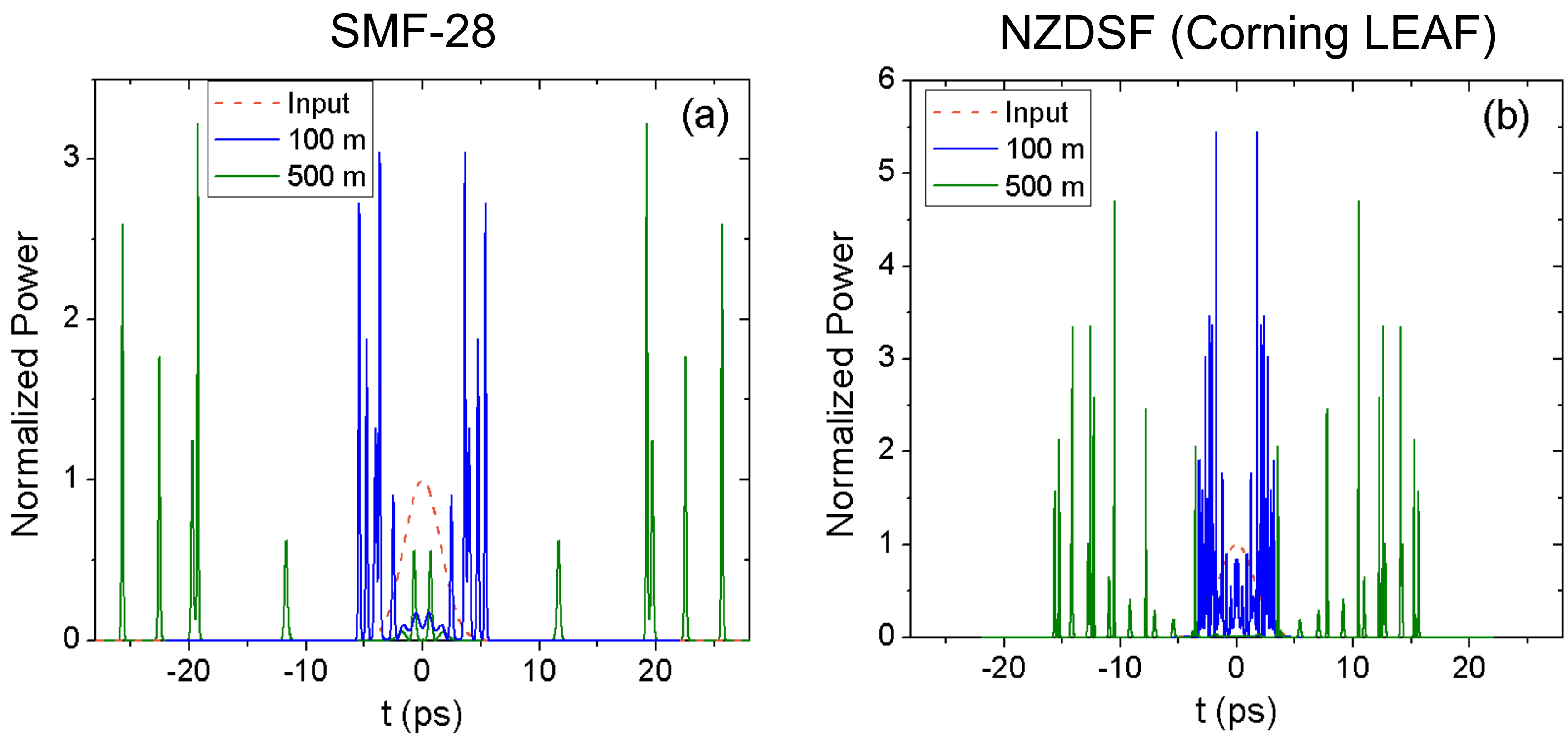
Due to pump-pulse distortion and long Gaussian tails of the signal pulses

Spreading of Pump Pulses

Input pump pulses: 5 ps, 2.5 nJ

Propagation Equation:

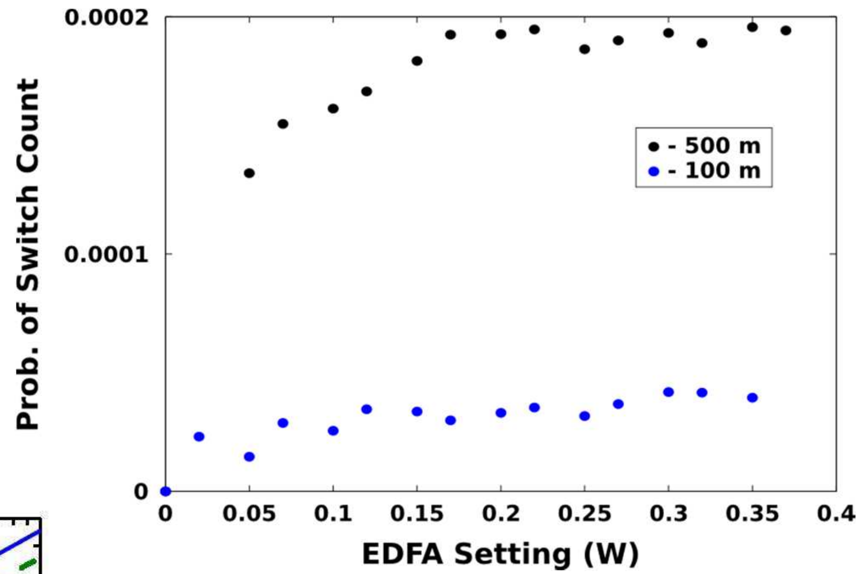
$$\frac{\partial A_j(z,t)}{\partial z} = -\alpha A_j(z,t) - \beta_j^{(1)} \frac{\partial A_j(z,t)}{\partial t} - \frac{i\beta_j^{(2)}}{2} \frac{\partial^2 A_j(z,t)}{\partial t^2} + i\left(\varrho P_{\|}(z,t) + \varsigma P_{\perp}(z,t)\right) A_j(z,t), \quad \text{for } j = 1, 2.$$

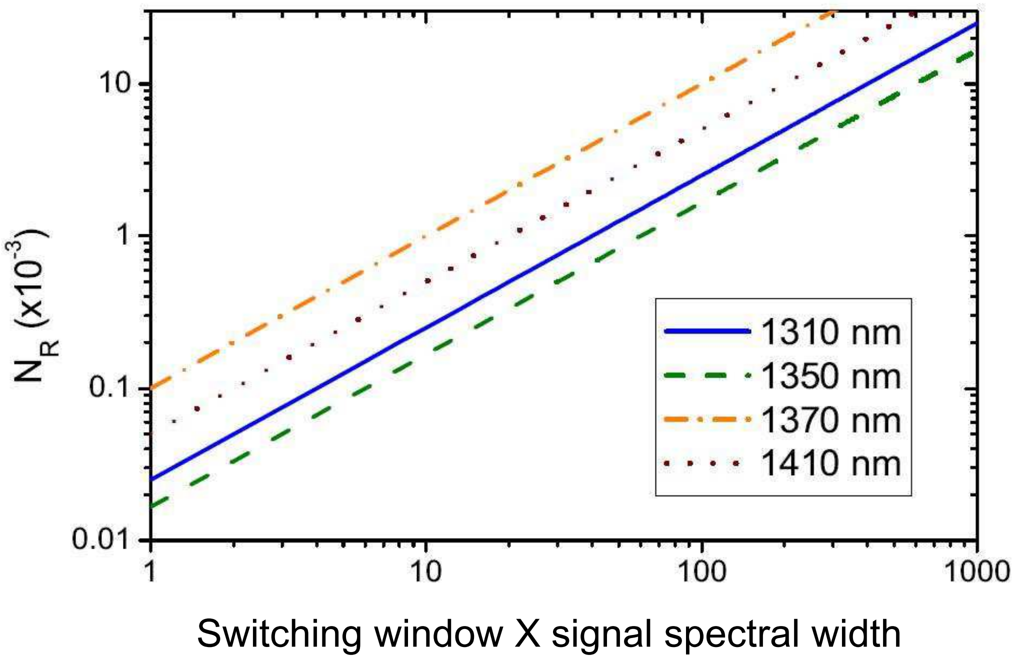


Quantifying Raman Noise

- Pump: 1550 nm, 5 ps, 2.5 nJ
- Fiber: 500 m, room temperature

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



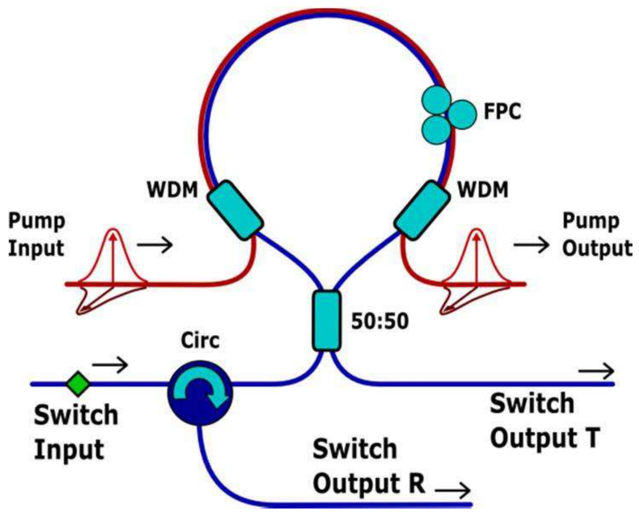


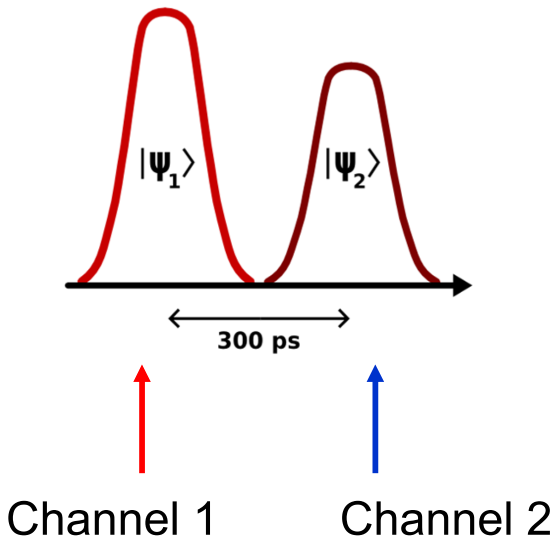
Negligible Raman is confirmed by theory, but need more data for a direct comparison

Huang & Kumar, NJP, to be submitted.

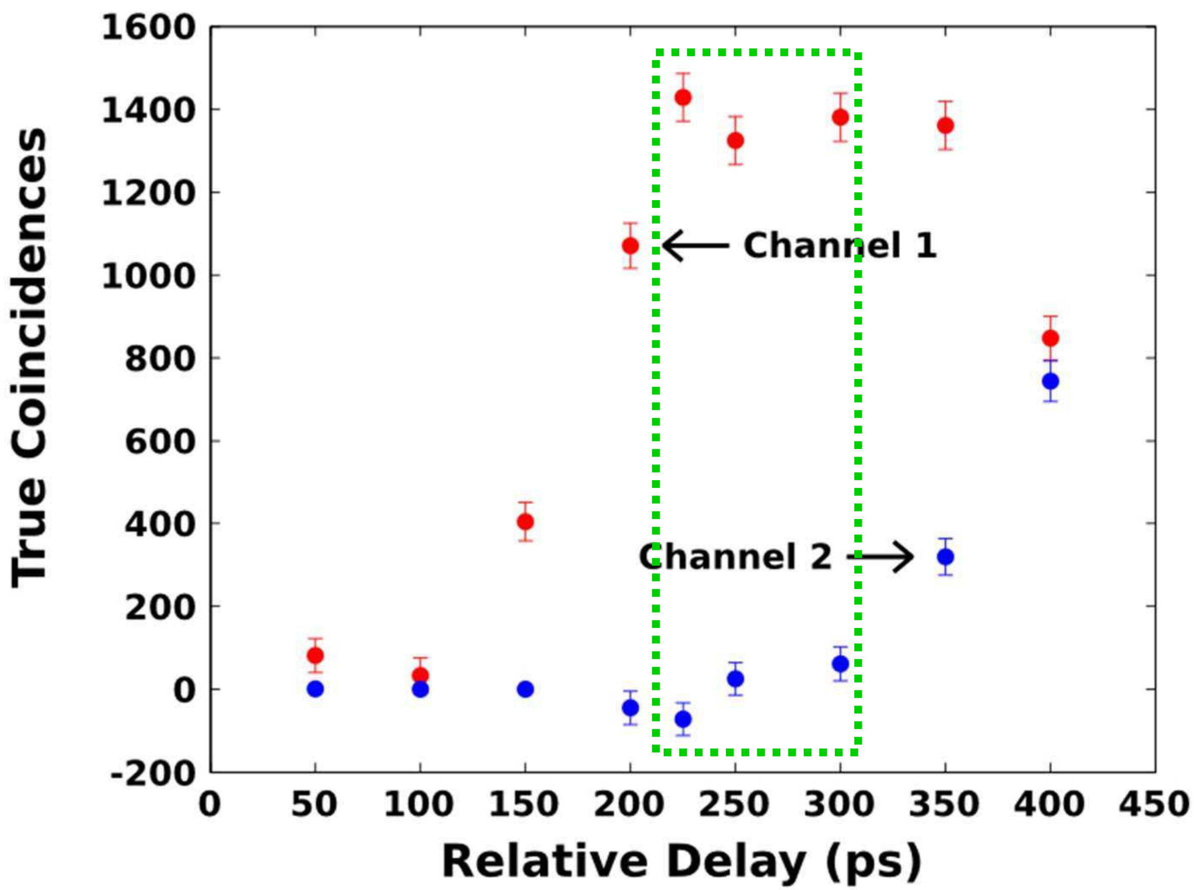
Coincidence (Quantum) Eye Opening

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

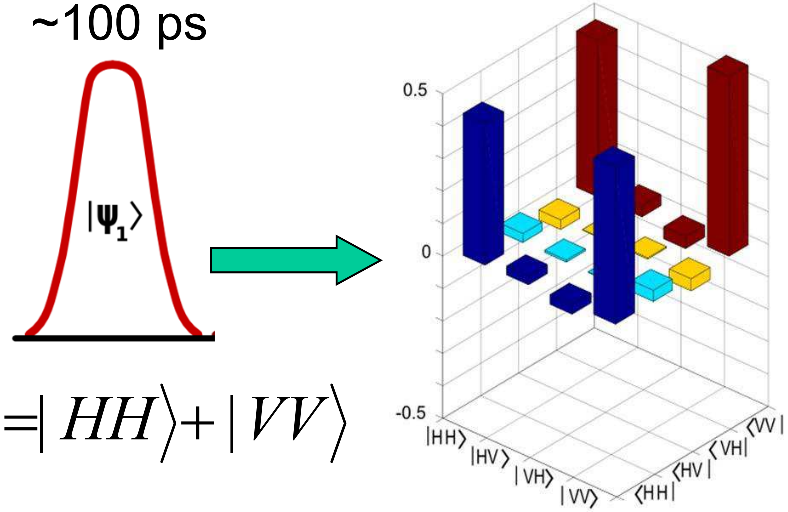




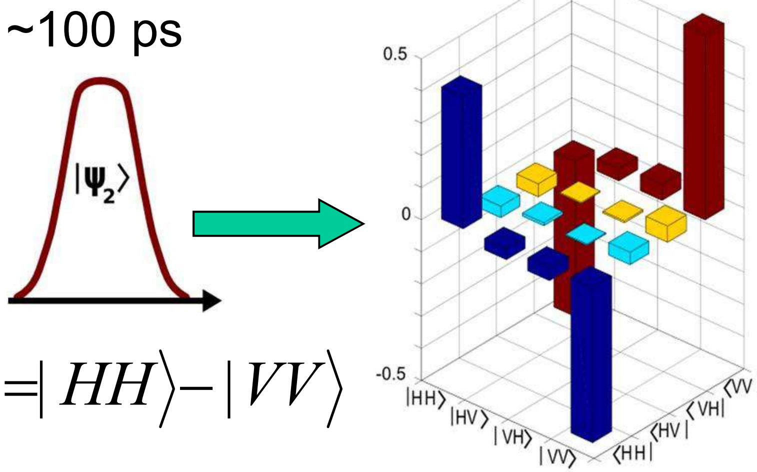
~100ps-wide
Quantum Eye



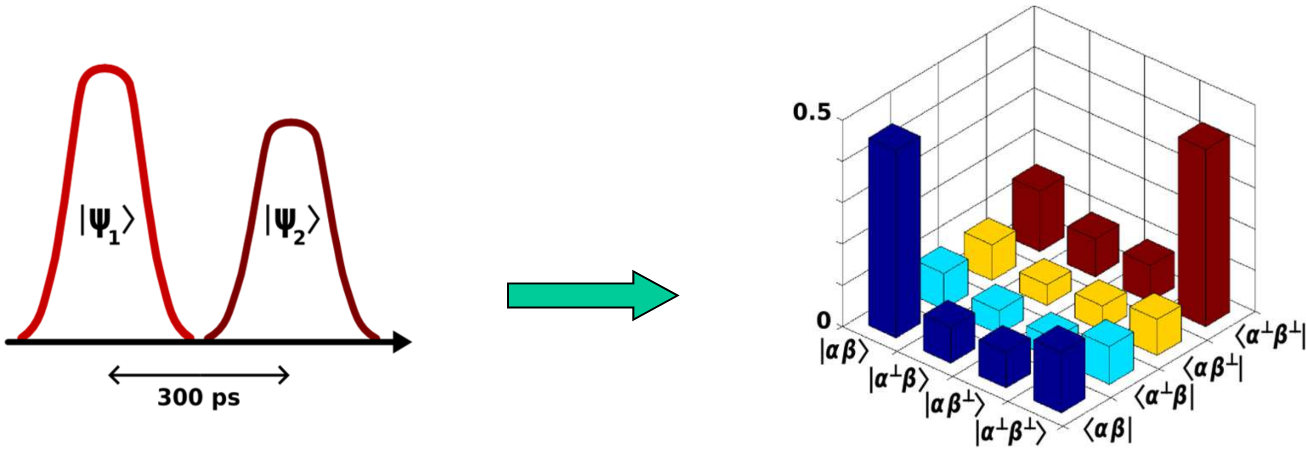
Time-Domain Multiplexed Quantum Data



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



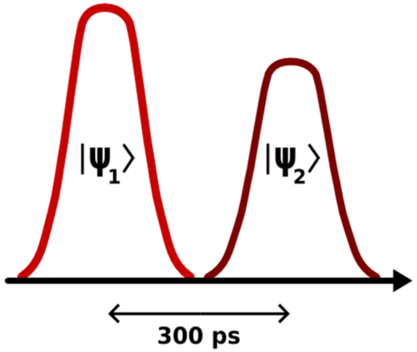
$$|\Psi_2\rangle = |HH\rangle - |VV\rangle$$



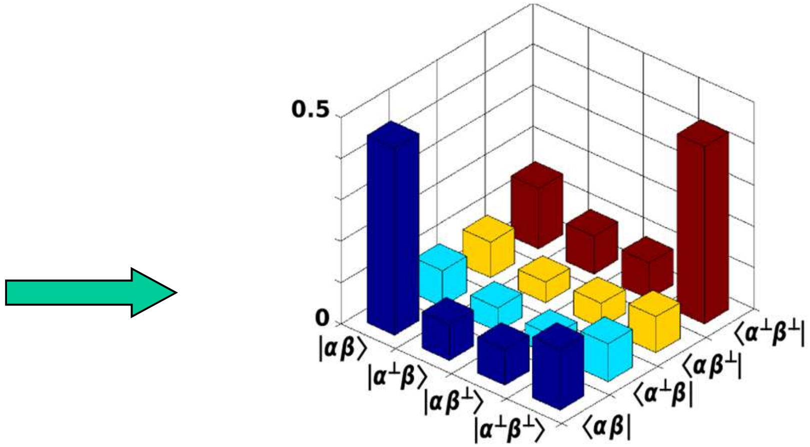
$$|\Psi_1\rangle\langle\Psi_1| + |\Psi_2\rangle\langle\Psi_2|$$

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

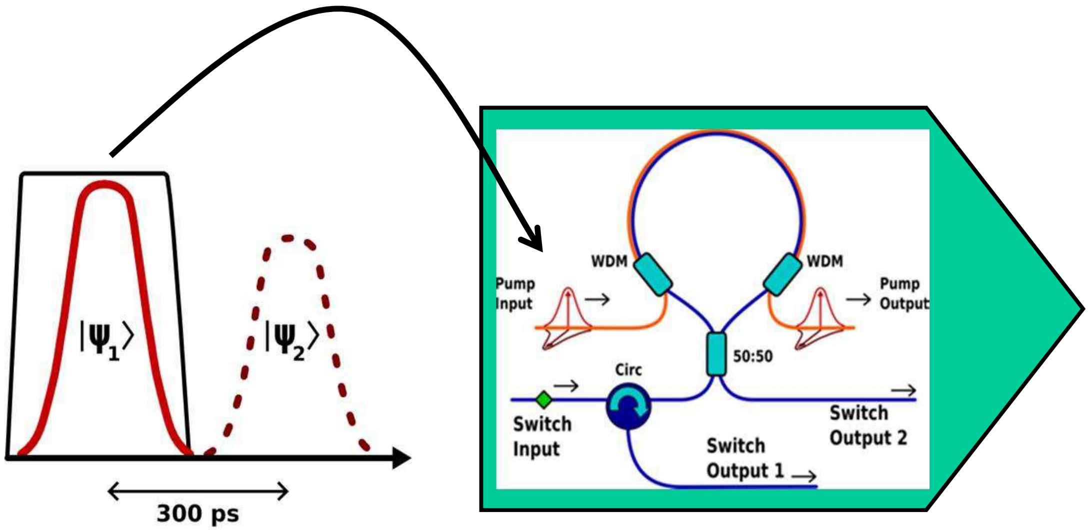
Time-Domain Demultiplexing of Ultrafast Quantum Channels

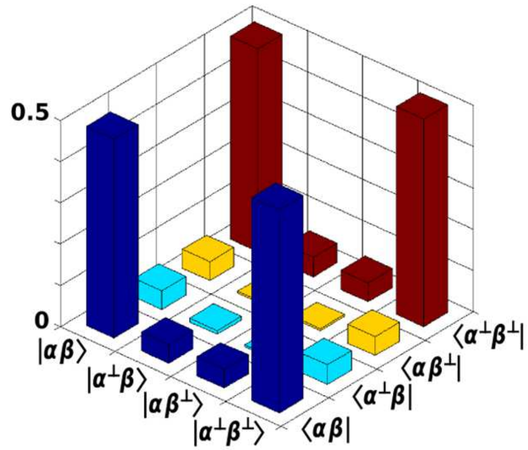


$$|\Psi_1\rangle\langle\Psi_1| + |\Psi_2\rangle\langle\Psi_2|$$



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

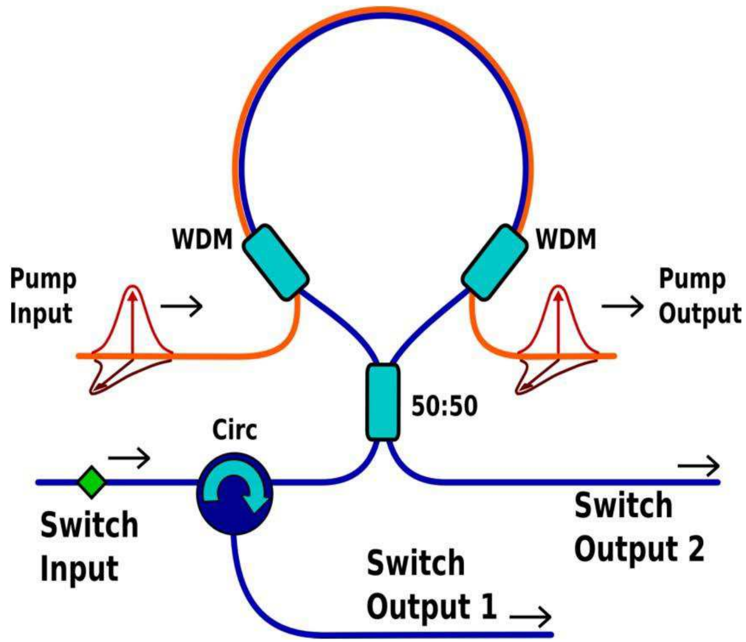




Fidelity to $|\alpha\beta\rangle+|\alpha^{\perp}\beta^{\perp}\rangle$ = 0.986

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

Switch Improvements: Loss



Loss	Current (dB)
WDMs	0.6
50:50	0.2
100m Spool	0.03
Splices	0.07
Total Output 1	**0.9**
Circulator	0.4
Total Output 2	**1.3**

With optimized components it should be possible to get the total loss down to ~ 0.2 - 0.3 dB per switching cycle.

Japanese Journal of Applied Physics **49** (2010) 052203 **REGULAR PAPER**

Design and Simulation of Silicon Waveguide Optical Circulator Employing Nonreciprocal Phase Shift

Ryohei Takei and Tetsuya Mizumoto

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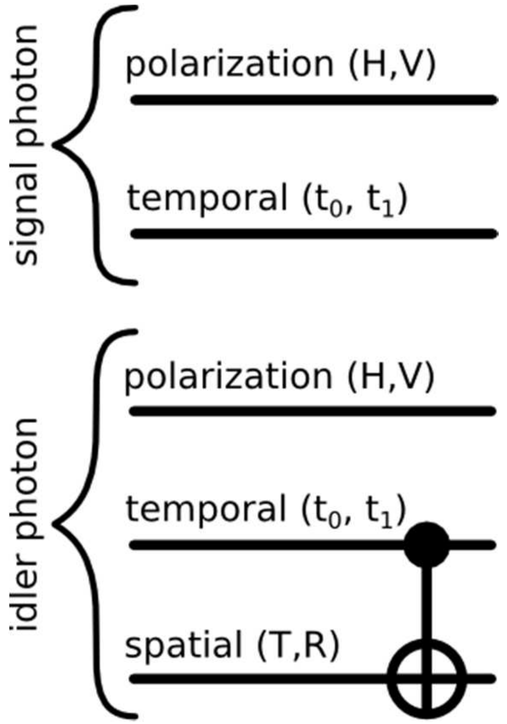
Jpn. J. Appl. Phys. **49** (2010) 052203

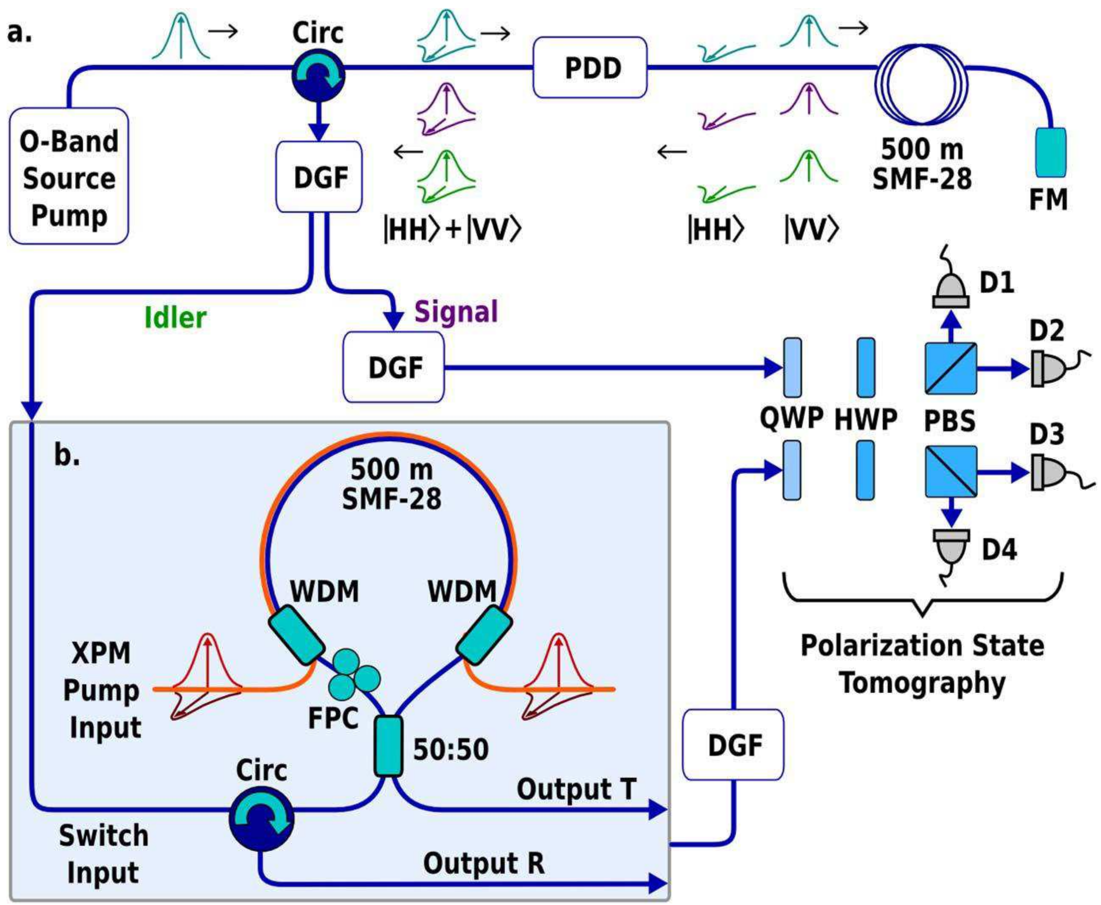
an insertion loss below 0.05 dB. Also, the three-port optical circulator exhibits a crosstalk below −20 dB with an insertion loss below 0.04 dB in a wavelength range between 1.53 and 1.57 μm. The total length of both types

Another Perspective: A Deterministic CNOT Gate

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

2-photon 5-qubit
hyper-entangled Hilbert space





On the idler photon, the temporal qubit acts as the control qubit and the spatial qubit acts as the target qubit.

Conclusions / Future Outlook

- Fiber-based nondegenerate entangled photon-pair source
  - Potentially field deployable source demonstrated with standard off-the-shelf telecom components
  - Demonstrated a practical source of Q-band (1310 nm) entanglement
  - Q-band entanglement survives robustly in active C-band (1550 nm) hardware
- XPM based switching platform for Q-band entanglement
  - First results on high fidelity switching of Q-band entanglement
  - Potentially very low loss (< 0.2-0.3 dB per switching cycle)
  - Potentially very high speed (10-100 GHz)
  - Demonstrated high-speed MUX / DEMUX of quantum data pattern
- Practical short-term (10's to 100's μs) quantum buffers, single-photons on demand, a practical near-term reality.