Photon Pair Production using non-linear waveguides

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Motivation

- Correlated photon-pairs are useful for applied and fundamental research:
  - Heralded single photons
  - Entangled pairs of qubits

Desirable features in a source

- high brightness
- low noise
- ability to engineer characteristics (mode size, frequencies, etc.)

Traditional Photon-Pair Sources

- Atomic Cascades
- Bulk non-linear crystals (e.g. BBO, KDP, KTP,..)

Relatively recent developments:

a) periodically pole bulk crystals (e.g PPLN, PPKTP)

b) better focusing regimes for more efficient collection

Emission is multi-mode and low overlap with single spatial mode

Waveguide Sources

Waveguides can be optical fibers or in an optical crystal.

Advantages:

- Can be engineered to achieve phase-matching over different wavelengths
- Overlaps well with single spatial mode (esp with optical fibers)
- Strong nonlinear effects due to pump confinement

Talk Outline

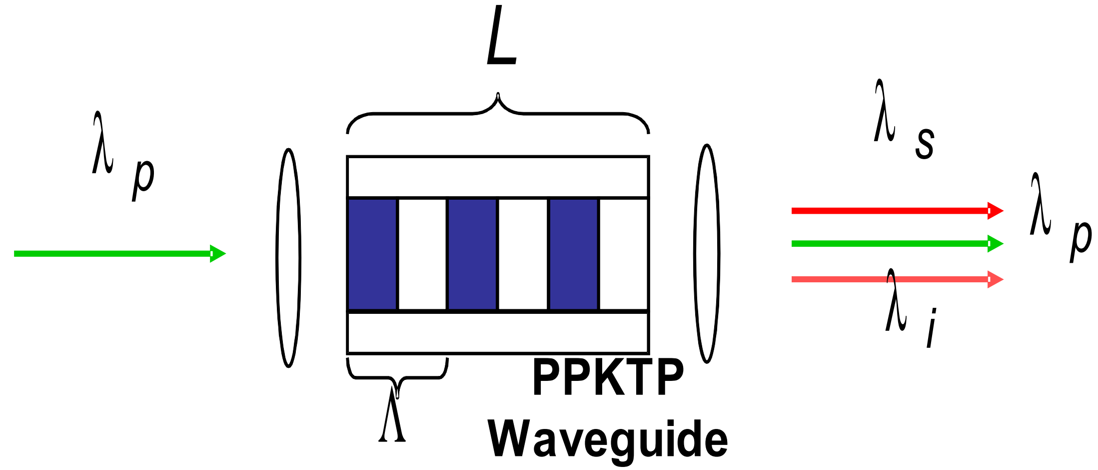
PPKTP waveguide

- Choice of Type-0 or Type-II
- Spectral characterization of emitted photons
- Factorability of emitted light

Solid Core Photonic Crystal Fiber (PCF)

- Phase matching conditions
- Techniques to improve collection efficiency
- Indistinguishable photons and polarization-entanglement

PPKTP Crystal Waveguide



Induced Polarization $\vec{P} = \varepsilon_o \chi^{(1)} \cdot \vec{E} + \varepsilon_o \chi^{(2)} : \vec{E}\vec{E} + \varepsilon_o \chi^{(3)} \vdots \vec{E}\vec{E}\vec{E}$

Phase Matching Conditions for pump, signal and idler photons (p,s,i):

Momentum Conservation

$$\vec{k}_s + \vec{k}_i = \vec{k}_p$$

Energy Conservation

$$\omega_s + \omega_i = \omega_p$$

$$\Rightarrow \quad k_s + k_i + \frac{2\pi\, m}{\Lambda} + k_{wg} = k_p$$

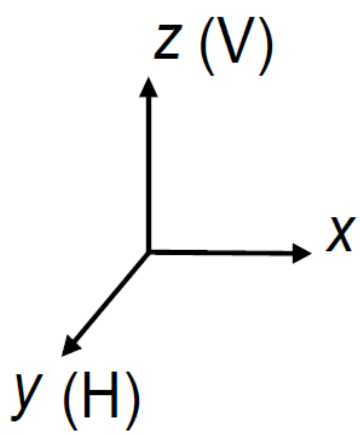
grating
m:harmonic order
$(-\infty : +\infty)$

Waveguide contribution

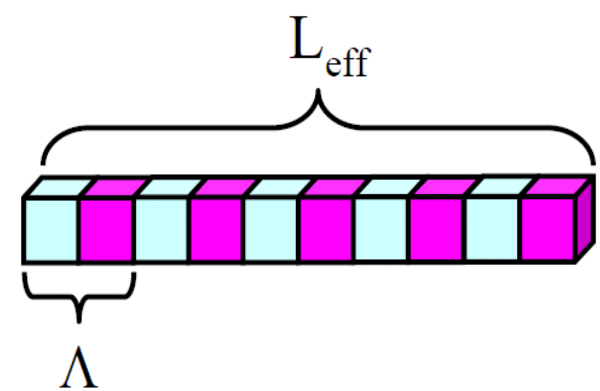
Waveguide design for type-0

Nominal Operational Values:

Length - 15 mm
Poling Period - 8.29 μm
Cross Section- 4 x 4 μm^2
Pump Wavelength- 532.2 nm
Pulse Duration- 5 ps
Rep. Rate- 80 MHz

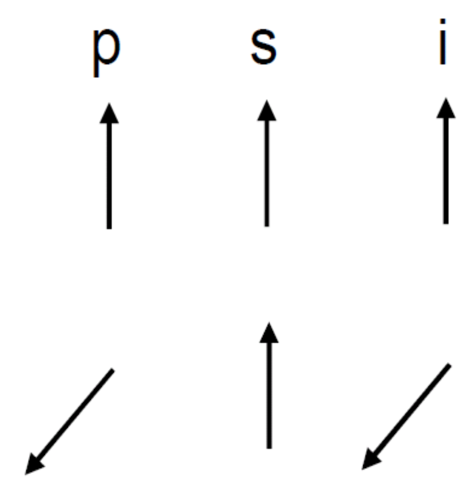


Temperature Controlled

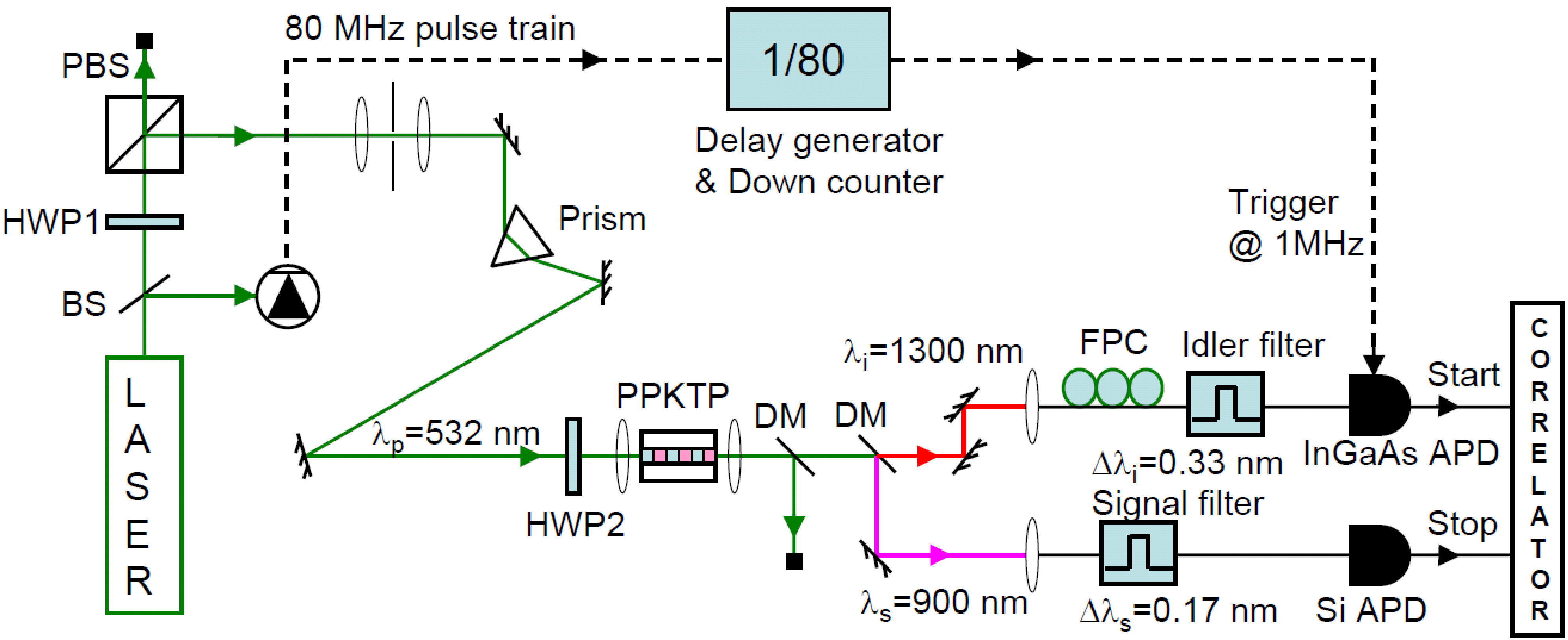


$$d_{eff} = \frac{2}{\pi} d_{33} \approx 8.7 \text{ pm/V}$$ Type-0

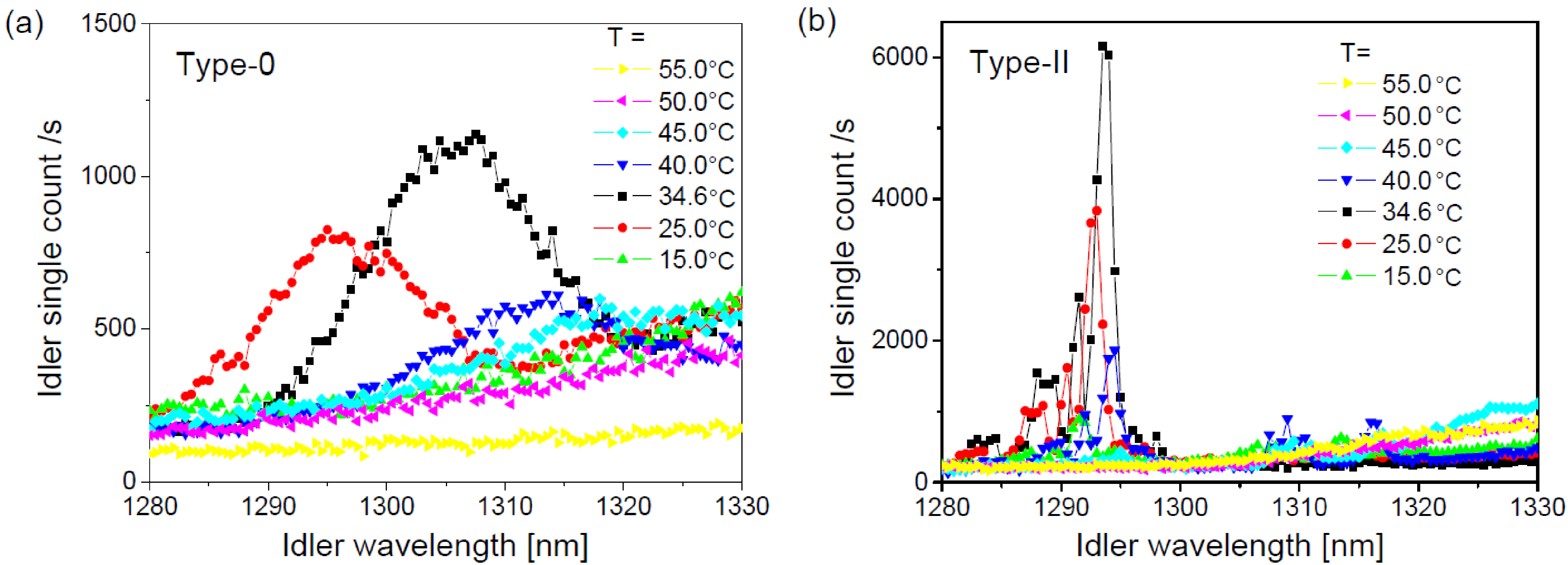
(also possible) $d_{24} = 7.6 \text{ pm/V}$ Type-II



Experimental Setup

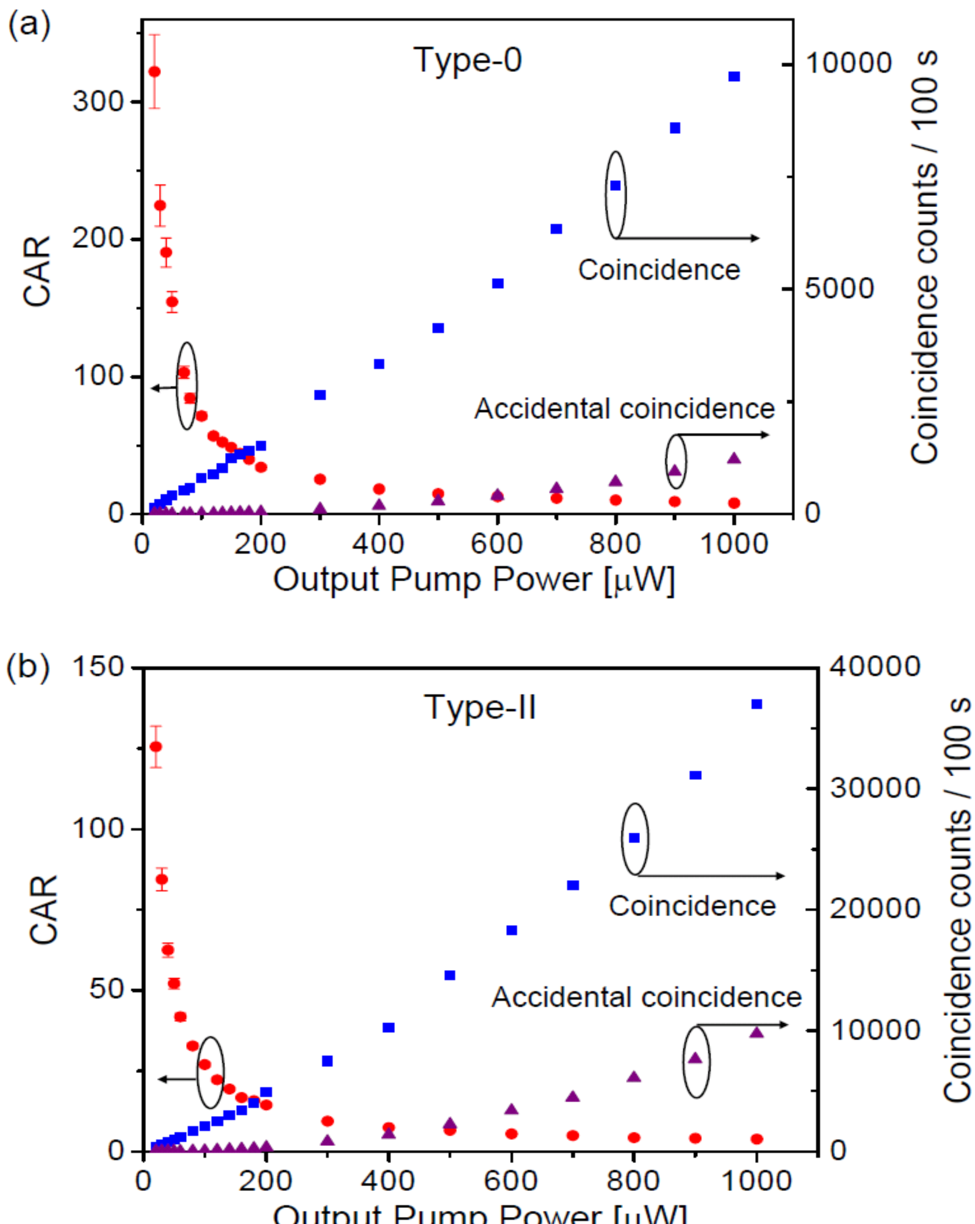


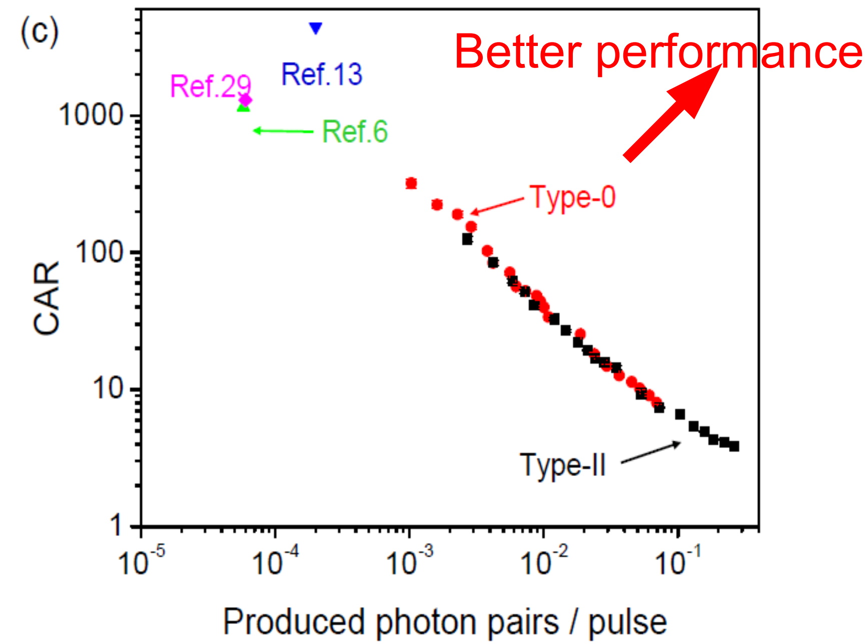
Single Photon Count Rate with Temperature



Same pump power at waveguide output ~ 50 mW
Same optimal temperature – 34.6 C (coincidence?)
Type II is brighter and narrower in bandwidth (why brighter?)

Coincidence Characterization





Ref 6. A. B. U'Ren et. al. Phys. Rev. Lett. 93,093601 (2004)
Ref 13. Q. Zhang et. al. Opt. Exp. 15, 10288 (2007)
Ref 29. S. D. Dyer et. al. Opt Exp 16, 9966(2008)

Poling period for type-II (?)

Phase matching conditions to solve:

$$\frac{2\pi n_z(\lambda_p)}{\lambda_p} = \frac{2\pi n_z(\lambda_s)}{\lambda_s} + \frac{2\pi n_z(\lambda_i)}{\lambda_i} + \frac{2\pi m_0}{\Lambda} + k_{wg},$$

$$\frac{2\pi n_y(\lambda_p)}{\lambda_p} = \frac{2\pi n_z(\lambda_s)}{\lambda_s} + \frac{2\pi n_y(\lambda_i)}{\lambda_i} + \frac{2\pi m_2}{\Lambda} + k_{wg},$$

type-II : $\lambda_p = 532.2\,\text{nm}$, $\lambda_s = 904\,\text{nm}$ and $\lambda_i = 1294\,\text{nm}$

Solution available when $m_0 = m_2 = 0$ and $k_{wg} = -0.1\,\mu\text{m}^{-1}$

type-II is phase-matched purely from waveguide geometry.

Poling period for type-0

type-0 : $\lambda_p = 532.2\,\mathrm{nm}$, $\lambda_s = 899.2\,\mathrm{nm}$ and $\lambda_i = 1304\,\mathrm{nm}$

Solution available when $m_0 = m_2 = 1$, $k_{wg} = -0.1\,\mu\mathrm{m}^{-1}$ and $\Lambda = 8.05\,\mu m$

Nominal value: 8.29

type-0 heralded single photon spectra

file:///mathematica/Phasematching/PPKTP/type0expt_n_model_spectrum.jpg

Bandwidth is consistent with poling length of 8 mm

type-II heralded single photon spectra

Bandwidth is consistent with crystal length of 14.5 mm

Spectral Correlations

K: Schmidt number
S: Entropy of entanglement

K & S grow monotonically with larger spectral correlation.

For an uncorrelated (factorable) state:

$$\Psi(\omega_s,\omega_i) = \psi(\omega_s)\varphi(\omega_i)$$

K=1 & S=0

two-photon state $\Psi(\omega_s,\omega_i)$

↓ Schmidt decomposition

$$\Psi = \sum_n \sqrt{\lambda_n}\,\psi_n(\omega_s)\,\varphi_n(\omega_i)$$

↓ $\sum_n \lambda_n = 1$

$$K = \frac{1}{\sum_n \lambda_n^2} \qquad S = -\sum_n \lambda_n \log_2(\lambda_n)$$

Factorability

To achieve factorability, the group velocities must satisfy the relationship:

crystal length

$$\gamma \frac{L^2}{2}\left(\frac{\partial k_p}{\partial \omega}-\frac{\partial k_e}{\partial \omega}\right)\left(\frac{\partial k_p}{\partial \omega}-\frac{\partial k_o}{\partial \omega}\right)+\frac{2}{\sigma^2}=0$$

constant

pump bandwidth

σL

Rewrite as:

$$\gamma \sigma L \Delta \nu_o^{-1}+\frac{4}{\sigma L \Delta \nu_e^{-1}}=0$$

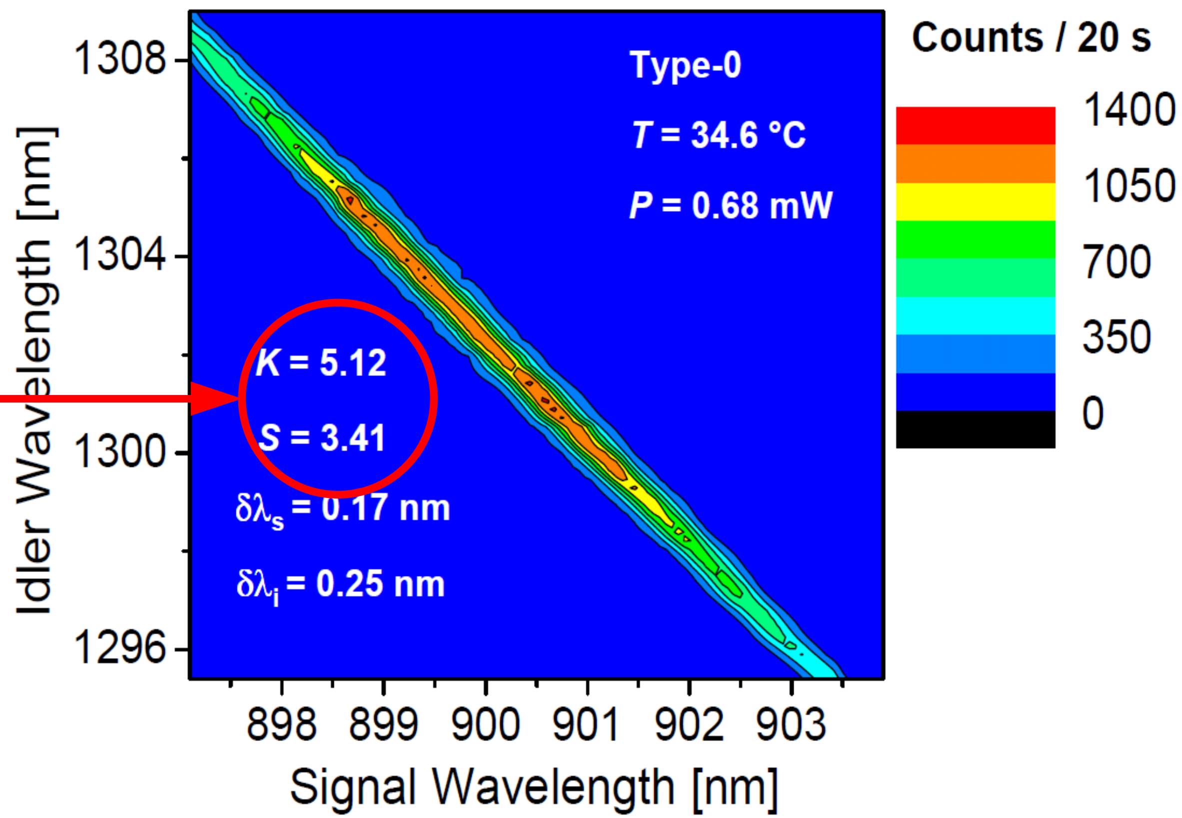
Unlikely to be satisfied by type-0

This is achieved if both terms are zero:

- When group velocity of (o-ray) photon matches that of pump
- When $\sigma L \gg \Delta \nu_e$

i.e. transit time difference between pump and e-ray photon must be much greater inverse pump bandwidth

type-0 coincidence spectrum



type-0 is highly spectrally entangled

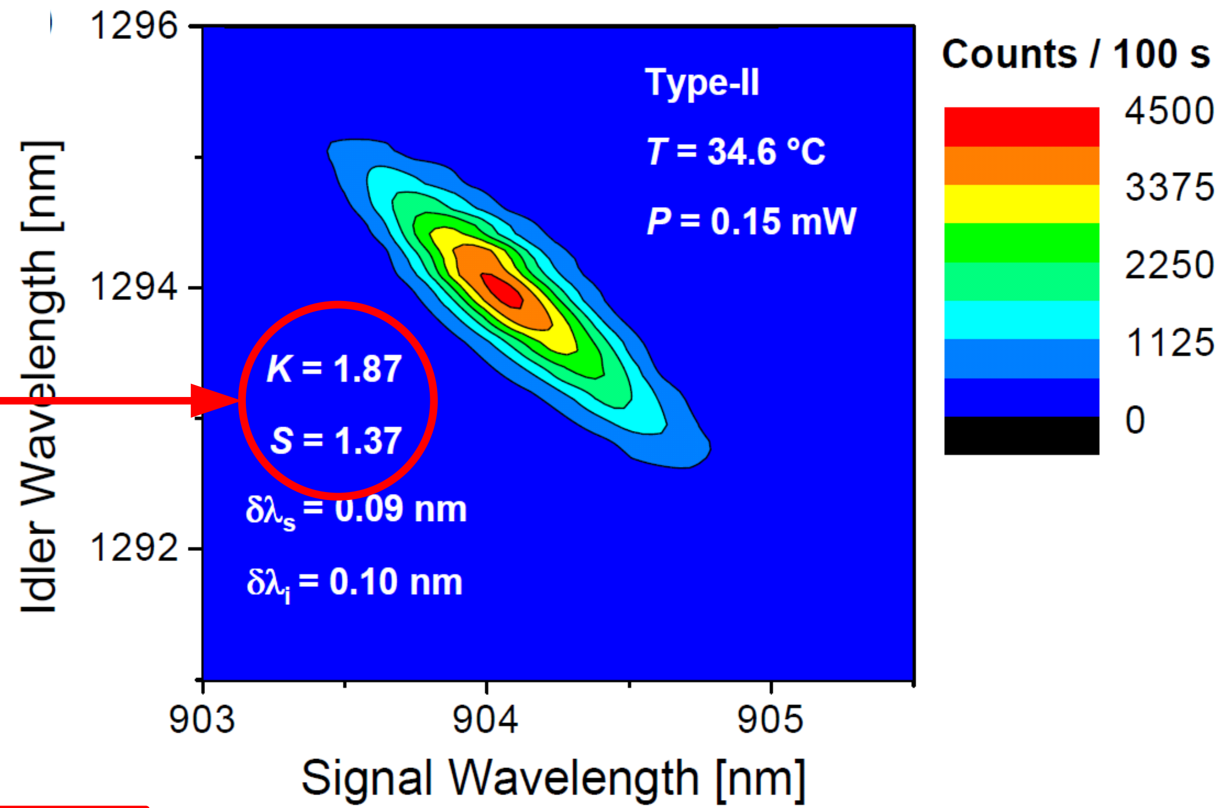
For a factorable state:

$$\Psi(\omega_s, \omega_i) = \psi(\omega_s)\,\varphi(\omega_i)$$

K=1 & S=0

type-II coincidence spectrum

type-II approaches
a factorable state
(why?)

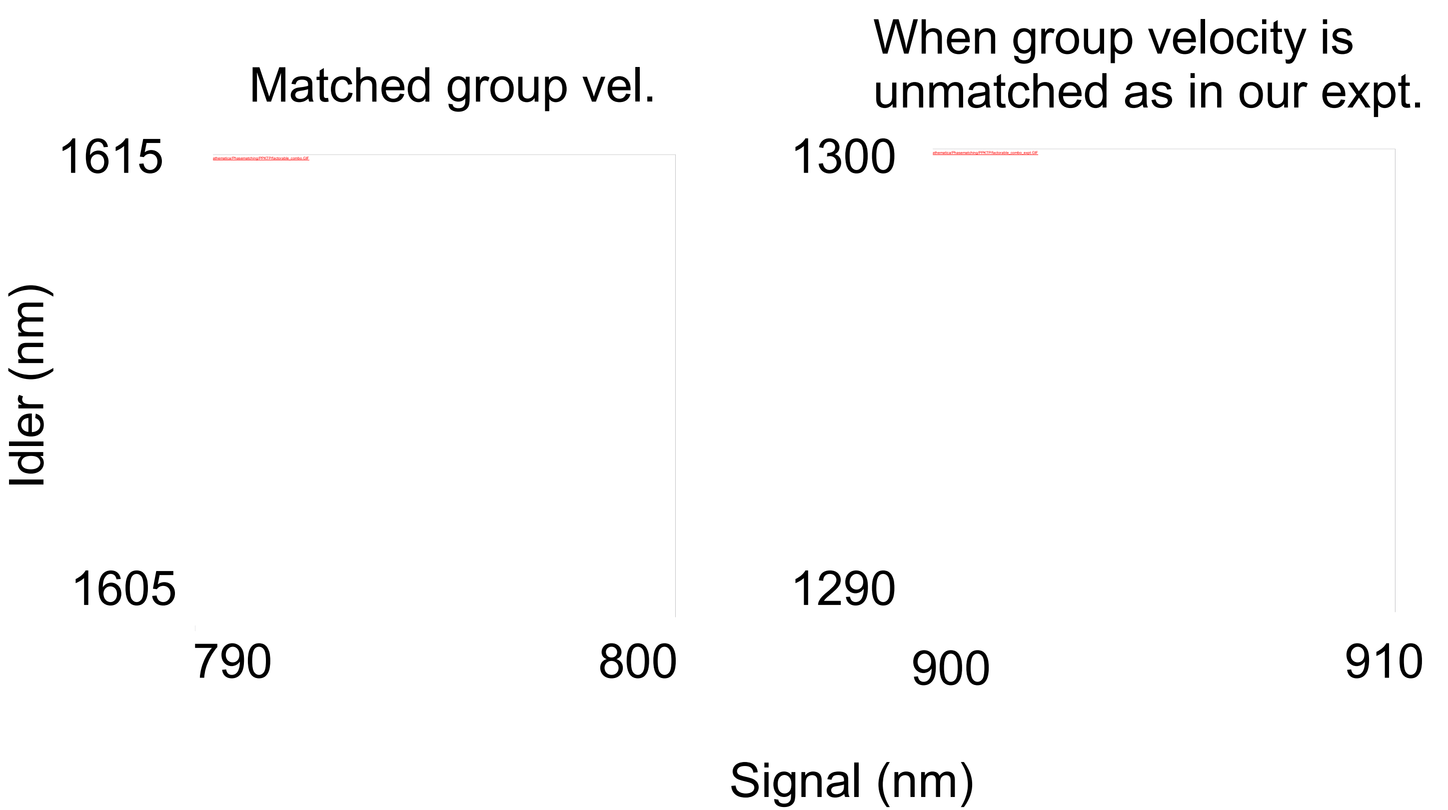


For a factorable state:

$$\Psi(\omega_s,\omega_i) = \psi(\omega_s)\varphi(\omega_i)$$

K=1 & S=0

type-II phase matching function



Factorability with waveguide length

file:///mathematica/Phasematching/PPKTP/js_wg_schmidtcombo.jpg

Experimental K value – 1.87
This corresponds to a 14.5mm long crystal (using model)

Conclusion

- **Why is type-II brighter?**

  Poling period irregular and not over entire crystal length, hence type-II has the stronger downconversion efficiency

- **Why does type-II have a narrower bandwidth?**

  Phase matching is more stringent in type-II which takes place over a bigger length

- **Why is the coincidence spectra of type-II more factorable?**

  Group velocity mismatch is much less in type-II

- **Why is the optimal temperature similar?**

  Not sure yet...more modeling required

Summary

Advantages of crystalline waveguides:

a. can be engineered (via poling or size)

b. can be bright

c. factorable states can be generated with appropriate engineering

d. phase-matching can take without poling

Challenges:

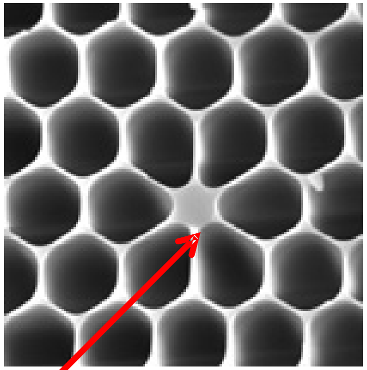
a. Poling period and length not consistent (?)

b. Challenging to couple light into and out of the waveguide

Solid Photonic Crystal Fibers

Induced Polarization: $\vec{P} = \varepsilon_o \chi^{(1)} \cdot \vec{E} + \varepsilon_o \chi^{(2)} : \vec{E}\vec{E} + \varepsilon_o \chi^{(3)} \cdot \vec{E}\vec{E}\vec{E}$

four-wave mixing uses $\chi^{(3)}$ non-linearity



Typically 1 micron diameter
(sensitive to drift)

Energy Conservation:

$$2\omega_p = \omega_s + \omega_i$$

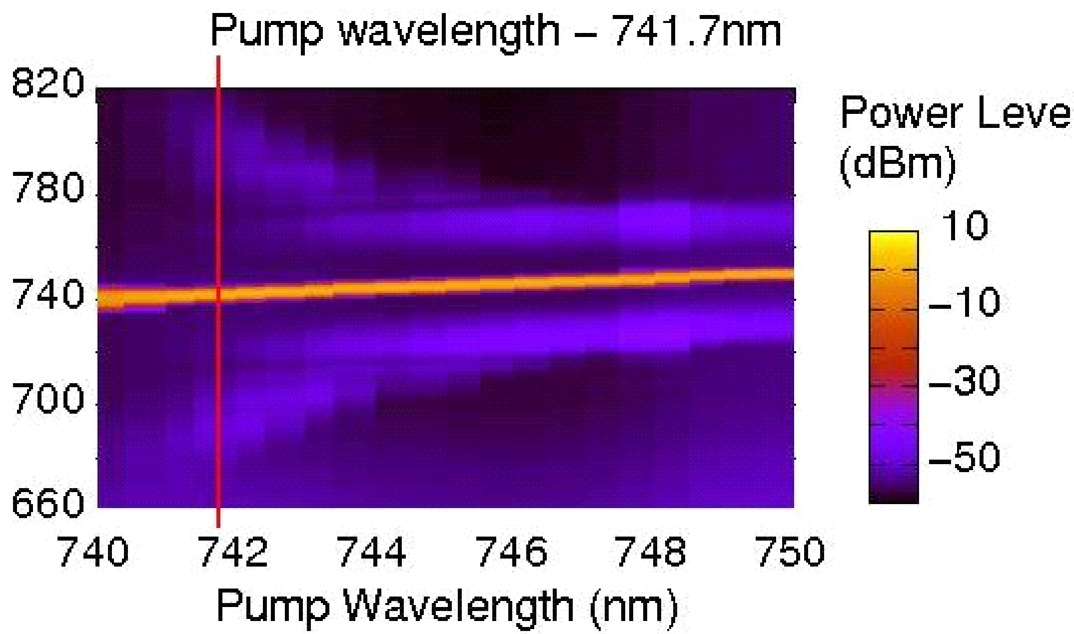
Momentum Conservation:

$$2k_p = k_s + k_i$$

Operates at room temperature.

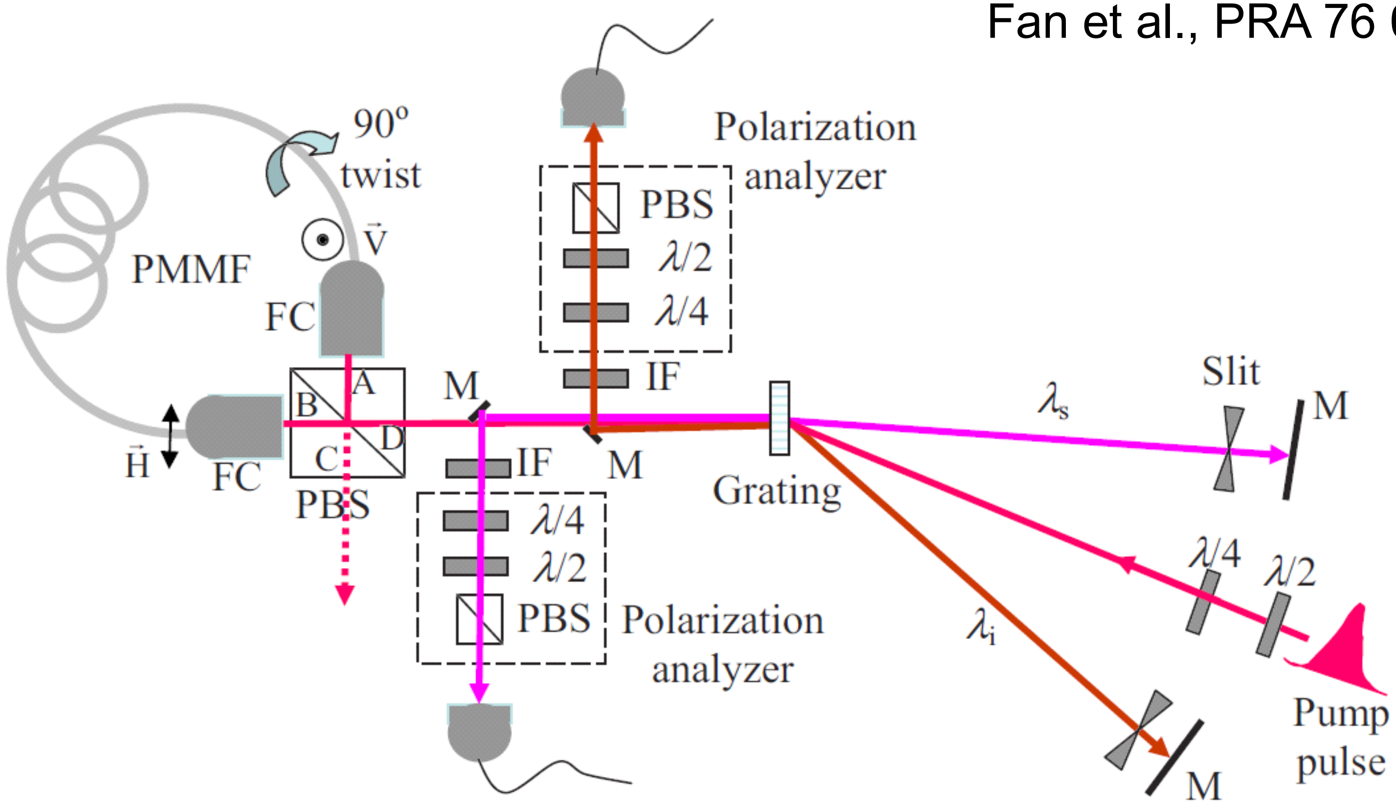
All photons generated in single spatial mode.

Four-Wave Mixing Spectrum



Example of previous implementation

Fan et al., PRA 76 043836 (2007)



Disadvantages:

i. Bulky and Lossy Spectrometer
ii. Requires Microscope Objectives (FC)
iii. Long path lengths – susceptible to drift

What's new

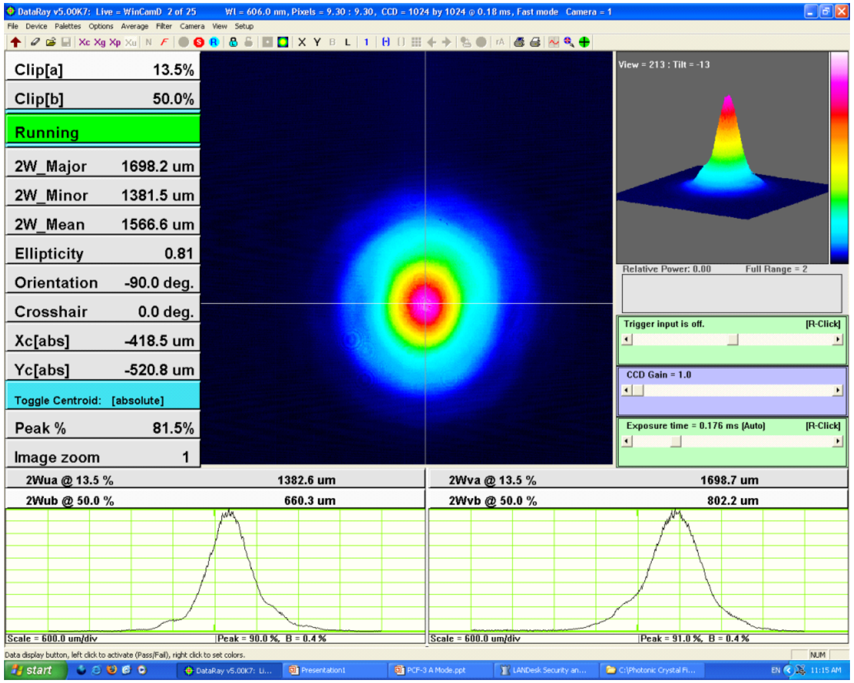
End Tapered PCFs

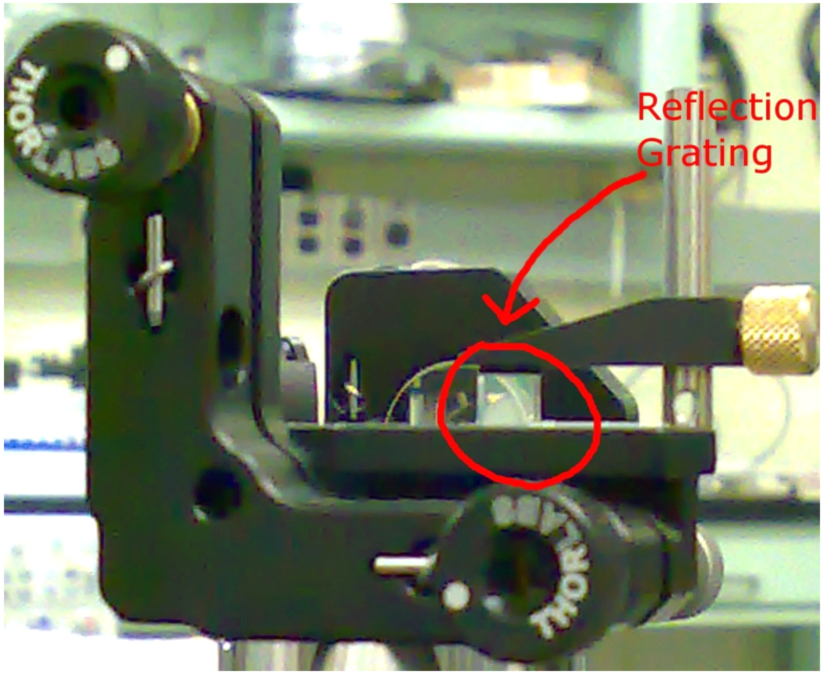
- Diameter of ends $\approx 15\,\mu$m
- Fiber Length = 1 m

Holographic Gratings

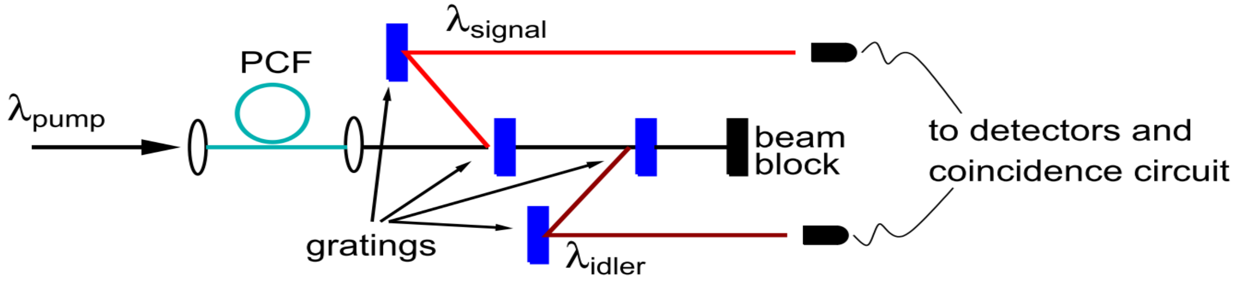
- Reflection Bandwidth = 0.15 nm
- Peak Reflection = 98%
- 5x5x3 mm - small!

Far-field mode for 801 nm light





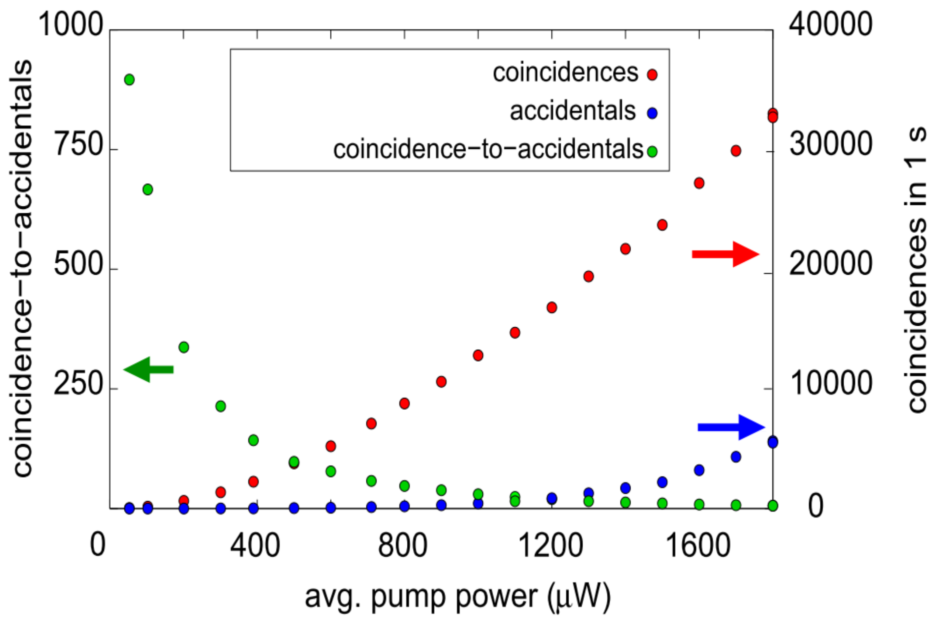
Loss Budget in Detecting Pairs

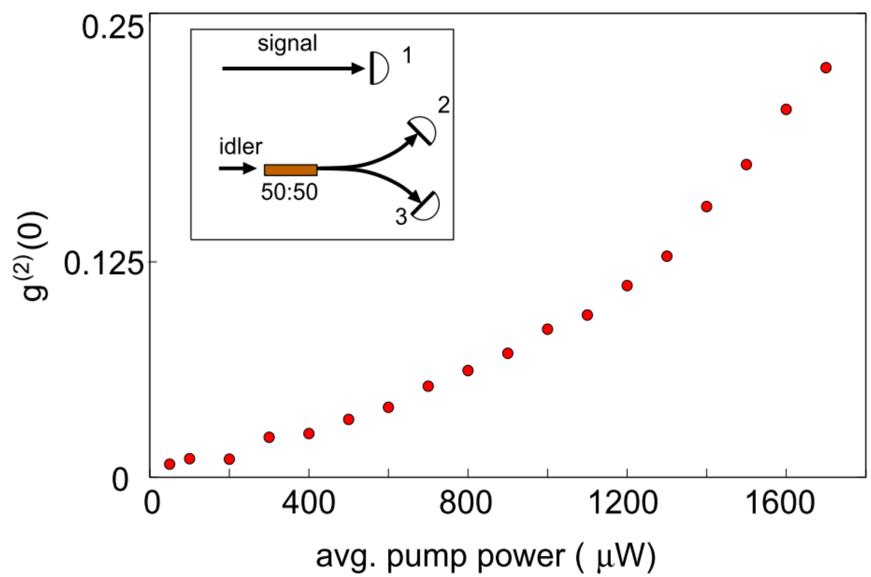


	Our source		Source: [18]		Source: [17]	
	S	I	S	I	S	I
collimating lenses	98	98	75	70	N.A.	
spectral selection	76	68	16	27	N.A.	
(extraction eff.)	(74)	(67)	(12)	(19)	(N.A.)	
fiber-coupling eff.	50	50	53	58	N.A.	
detector eff.	60	50	60	50	N.A.	
Single Photon Det. Eff.	22	17	4	6	5	5
Photon-pair Det. Eff.	4		0.2		0.25	

[18] Goldschmidt et al, PRA 78, 013844 (2008), [17] Fulconis et al, PRL 99, 120501 (2007)

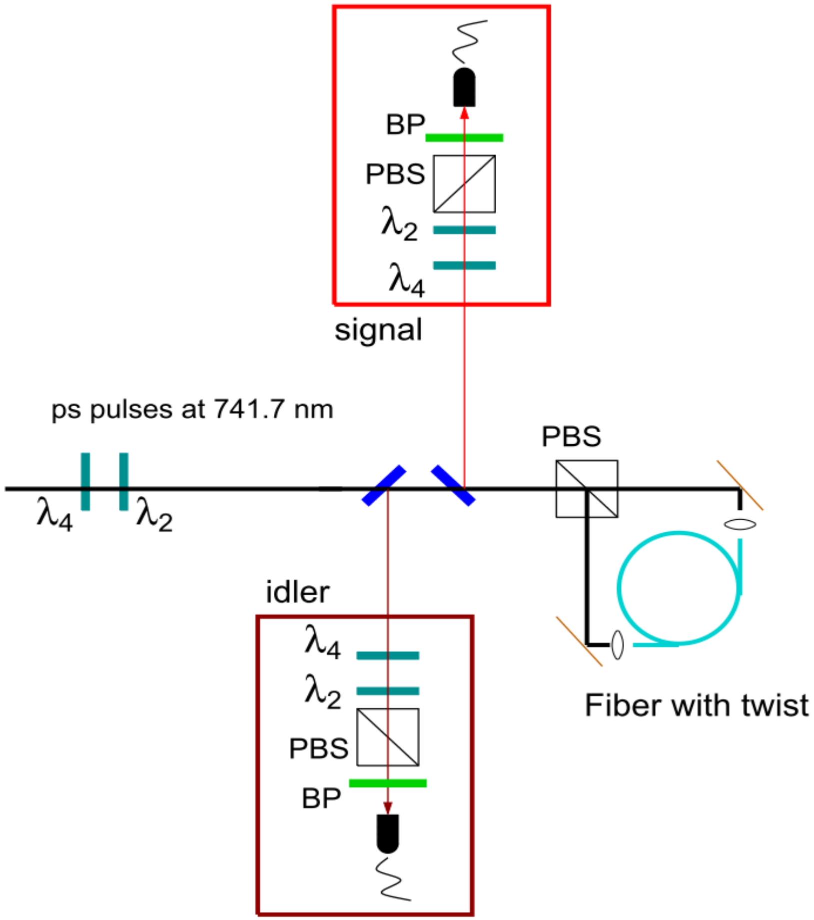
Photon-pair Purity

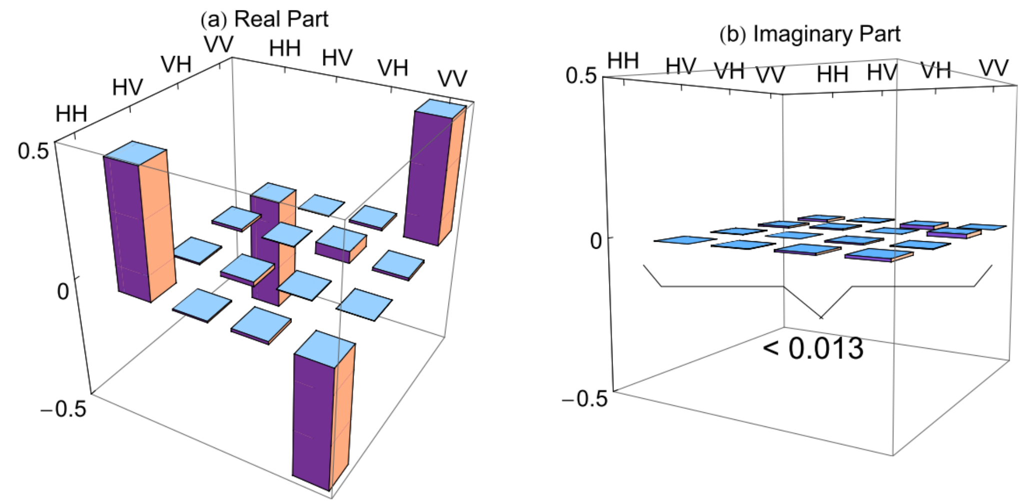




$g^{(2)}(0) = 0$ for 1 pair per pulse

Generating polarization-entangled photon-pairs





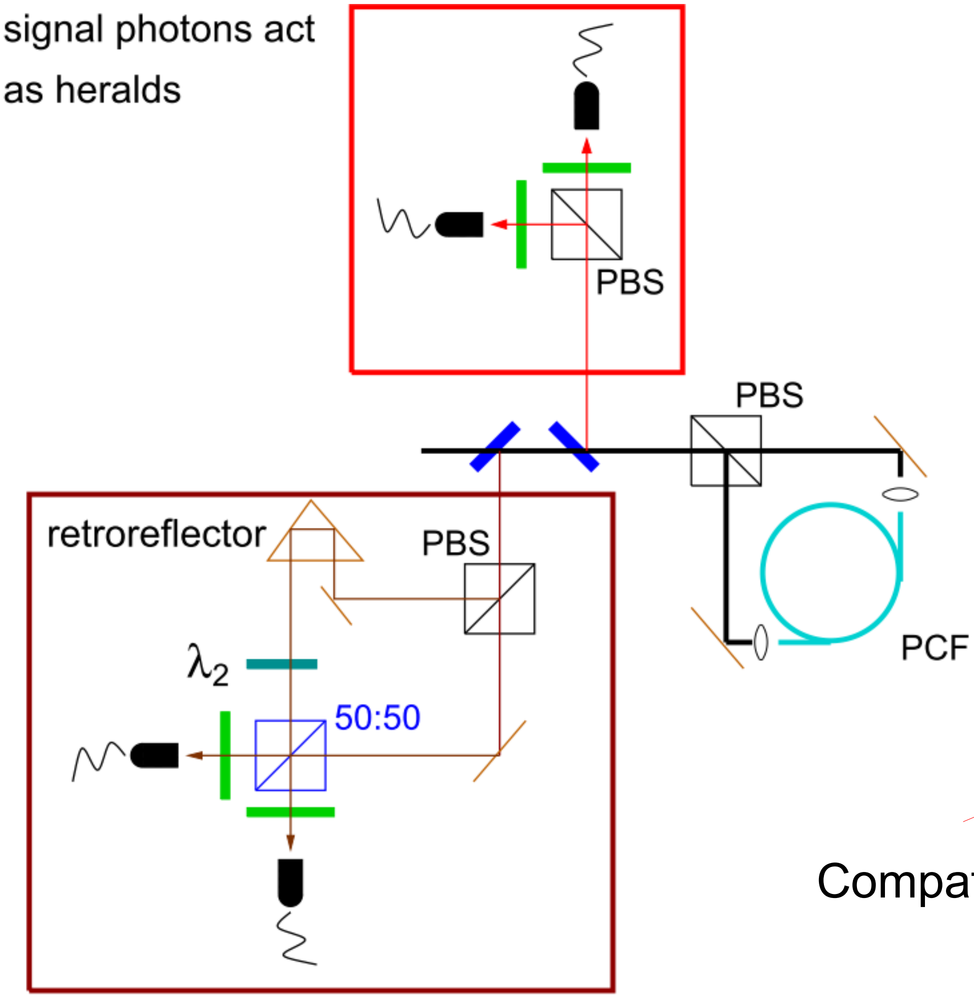
$$\Phi^- = \frac{1}{\sqrt{2}}(|HH\rangle - |VV\rangle)$$

Entangled Source Characteristics

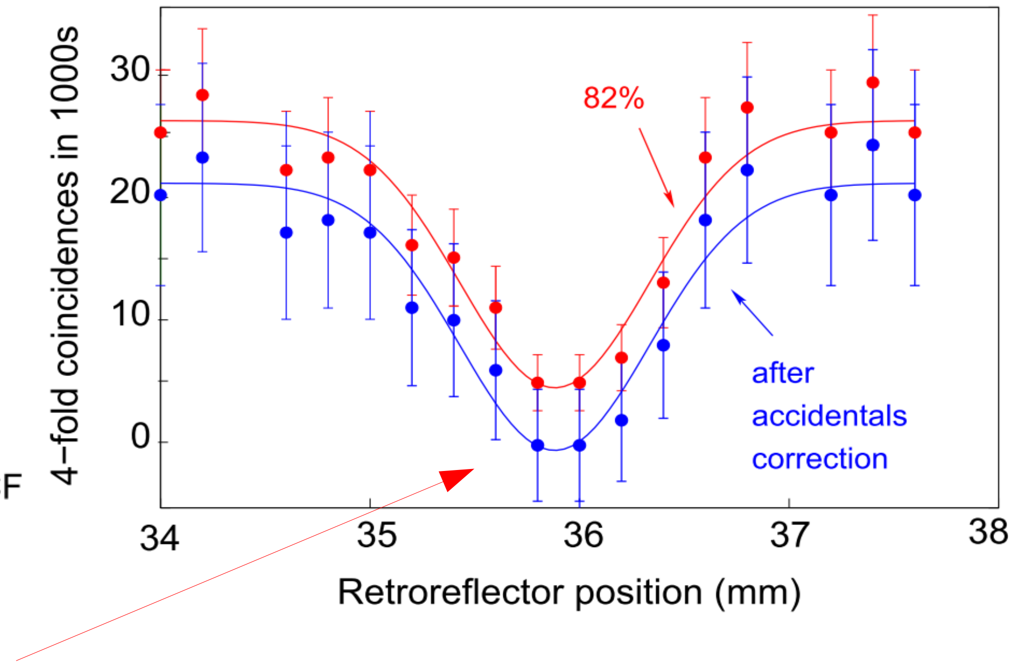
- 2800 pairs/s/mW
- Tangle=92 ± 2 %
- Fidelity=97 ± 1 %

Generating Heralded Indistinguishable Photons

signal photons act as heralds



HOM apparatus for idler photons



Compatible with unit visibility

Summary

- PCFs are becoming a robust alternative to SPDC in producing heralded pairs and entangled photonic qubits
- These sources work at room temperature
- End-tapered fibers allow use of cheap and simple lenses to couple light into and out of the fiber
- Collection Efficiency and Stability is improved by end-tapered fibers

Future Directions:

- Better Coupling Efficiencies
  - Factorable states with PCFs?
- Continuous-variable entanglement?

Joint Spectrum with Factorable State

file:///mathematica/Phasematching/PPKTP/jointspectra.gif