Generation of pure photons in an optical fibre

Jeff Lundeen, Offir Cohen
Peter Mosley, Hendrik Coldenstradt, Graciana Puentes, Brian Smith, Ian Walmsley
Spontaneous FWM

- Two pump photons are spontaneously converted into two sideband photons in a $\chi^{(3)}$ material.
- Small core size ($\rightarrow$ high intensity) and long interaction length compensate for small $\chi^{(3)}$ vs. the $\chi^{(2)}$ in crystals.

Energy is conserved…

- $\omega_{\text{Pump}}$ → $\omega_s$
- $\omega_{\text{Pump}}$ → $\omega_i$

… as well as momentum

- $k_s$ → $k_i$
- $k_{\text{PUMP}}$ → $k_{\text{PUMP}} \propto 1/L$

Heralded Single-Photons

- Discrete Variable measurement-based quantum-computing requires heralded photons and a quantum memory.
- High visibility Hong-Ou-Mandel interference is critical for optical quantum logic gates. For this we need photons in a pure state.
The Two-photon Spectrum

- Energy and momentum conservation create correlations between the two photons.

\[ |\psi\rangle \propto \int d\omega_s d\omega_i f(\omega_s, \omega_i) a^\dagger(\omega_s) a^\dagger(\omega_i) |\text{vac}\rangle, \]

- Single photon detectors do not have fs time- or nm spectral-resolution
- This leads to a fundamental problem
Space-time entanglement between signal and trigger photons leads to timing and frequency jitter between photons from the two sources, even using very short pump pulses.

\[
\text{Visibility} = \text{Tr}(\hat{\rho}_1 \hat{\rho}_2) \approx \text{Tr}(\hat{\rho}^2) = \text{Purity}
\]
The goal is a factorable joint spectrum: 
\[ f(\omega_s, \omega_i) = h(\omega_s) \cdot g(\omega_i) \]

\[ |\psi\rangle = \frac{1}{(2\pi)^2} \int d\omega_s d\omega_i f(\omega_s, \omega_i) \hat{a}_s^\dagger (\omega_s) \hat{a}_i^\dagger (\omega_i) |\text{vac}\rangle \]

With a single pump beam we can make the following approximation:

Pump envelope function
\[ \alpha(\omega_s, \omega_i) \]

Fibre function
\[ \phi(\omega_s, \omega_i) \]

Joint spectral amplitude
\[ f(\omega_s, \omega_i) \]

fixed at 45°

\[ \theta_{\|} = -\arctan(\tau_s/\tau_i) \]

90° < \theta_{\|} < 180° for a factorable state

Optics Express, 15, 14870-14886 (2007) with U'Ren and Raymer

Design the fiber to have the correct dispersion for a factorable state
Pure photons in SPDC

- With careful choice of dispersion in a $\chi^{(2)}$ crystal we have engineered the modes the photons are emitted into:

Experimental Joint Spectrum

- Heralding efficiency up to 44%
- Four-photon count rates as good as the best sources but with 1/10 the pump power. (currently get 60 /s with 300 mW/crystal)
- High quality interference with no filters
- Broadest bandwidth heralded photons

Drawbacks:
  - bulk source (hard to couple to fibers)
  - limited to natural dispersion of nonlinear crystals

[Graph: Hong-Ou-Mandel dip]

Purity > 95%

Fibre sources of pure photons

- We modelled the dispersion in a solid-core microstructured fiber
  Optics Express, 15, 14870-14886 (2007)

- Any orientation of the phasematching function is possible:
  ➢ factorable states, frequency correlated or anti correlated states
Spontaneous FWM Spectrum

- we record the spectrum of generated light and measure the idler and signal wavelengths.
Finding the right fibre

- At the factorable point, $\omega_i$ is constant as $\omega_{pump}$ is varied.

Fibre function:

Idler

PCF: Crystal Fibre NL-1.8-750

Signal

hand fit to step model

Theoretical Joint Spectrum

Predicted Purity = 86% to 91%
Polarization Test of Purity

\[ R(\theta) = (1-P) + (1+P) \cdot \cos(2\theta)^2 \]

where \( P \) is the purity.

\[ |\Psi_{4\gamma}\rangle = |H_{\text{red}}V_{\text{red}}H_{\text{yellow}}V_{\text{yellow}}\rangle \]
Checking the purity

- Singles show that both beams are unpolarized
- The two-folds show regular polarization curves
- The four-folds exhibit non-classical interference

\[ |\Psi_1\gamma\rangle\langle\Psi_1\gamma| = |H_{\text{red}}\rangle \langle H_{\text{red}}| + |V_{\text{red}}\rangle \langle V_{\text{red}}| \]

\[ |\Psi_2\gamma\rangle = |H_{\text{red}}H_{\text{yellow}}\rangle + |V_{\text{red}}V_{\text{yellow}}\rangle \]

\[ |\Psi_4\gamma\rangle = |H_{\text{red}}V_{\text{red}}H_{\text{yellow}}V_{\text{yellow}}\rangle \]

Purity = 82% ± 2%
Summary

• Modal design of photons is possible with four wave mixing.

• Microstructured nonlinear sources (e.g. PCF) allow us to directly engineer the spectral properties of the photons.

• Generation of heralded unfiltered pure-state photons has been demonstrated in a waveguide → integrated optical circuits → scalable quantum information.

• A wide range of states are possible in the same fibre: factorable, ultra-broadband, frequency correlated, frequency anti-correlated.
Just the facts

**Fibre:**
Crystal Fiber NL-1.8-750  
Length=40cm  
Core diameter=1.75 μm  
Fill fraction=50%

**Pump:**
0.7 mW per pass  
\( \lambda_p = 785 \text{ nm} \)  
\( \Delta \lambda_p = 8 \text{ nm} \)  
76 MHz

**Photon Pairs:**
\( \lambda_i = 860 \text{ nm} \)  
\( \Delta \lambda_i = 2 \text{ nm} \)  
\( \lambda_s = 720 \text{ nm} \)  
\( \Delta \lambda_s = 8 \text{ nm} \)  
Coinc = 15000 /s  
4-folds = 3 /s  
Accidentals/coinc < 1/25

Experimental generation of pure state photons in SPDC:  

Engineering spectral correlations in SFWM in fibres:  

Past demonstrations of pair generation in fibres  
Filtering

- Spectral filtering can remove correlations by making the photon duration larger than the timing jitter $w_s$

\[ S(\omega_s, \omega_i) = \left| f(\omega_s, \omega_i) \right|^2 \]

![Diagram of spectral filtering with interference filters IF1 and IF2, and wavelength and signal wavelength plots]