Pulse Shaping of Entangled Photons

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PHYS 522/ECE 695 Lecture on Entanglement

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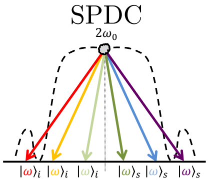
Time-Frequency Entangled Photons

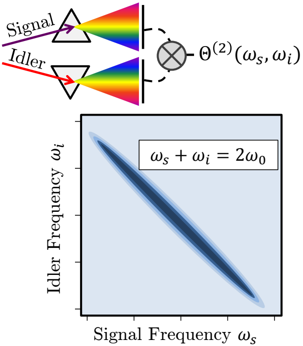
- Biphoton state:

$$|\Psi\rangle = \int d\Omega\, \phi(\Omega) |\omega_0 + \Omega\rangle_s |\omega_0 - \Omega\rangle_i$$

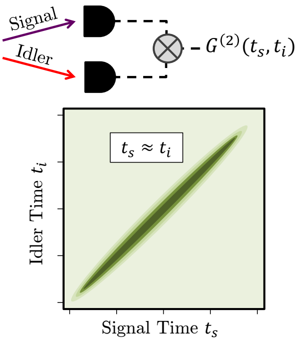
- Simultaneous time and frequency correlations:
  ⇒ Example of EPR paradox!



Frequency Correlation

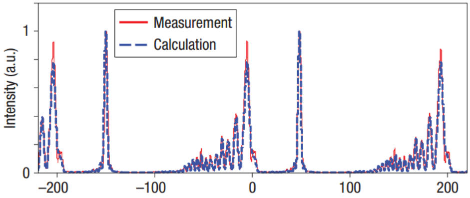


Time Correlation



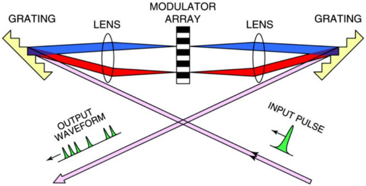
Classical Pulse Shaping

- Classical pulse shaping allows configurable waveform control. →
- Based on parallel manipulation of frequency components separated in space.
- Example of arbitrary waveform generation. ↓



Z. Jiang *et al.*, Nat. Photon. **1**, 463 (2007).

$4f$ Pulse Shaper

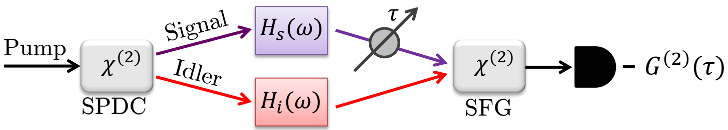


WaveShaper 1000S

Finisar WaveShaper 1000S

- Bandwidth: 1527-1567 nm
- Resolution: 10 GHz
- Complexity: 500

The Biphoton Wavepacket



- Use sum-frequency generation for fs-scale timing resolution.
- Probability of detecting the signal a time τ after its partner idler is proportional to the Glauber correlation function:

$$G^{(2)}(\tau) = \langle\Psi|\hat{E}_i^{(-)}(t)\hat{E}_s^{(-)}(t+\tau)\hat{E}_s^{(+)}(t+\tau)\hat{E}_i^{(+)}(t)|\Psi\rangle = \psi^*(\tau)\psi(\tau).$$

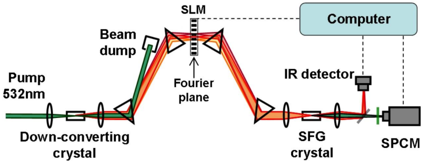
- Using the the quantum state on the last slide, we find:

Biphoton Wavepacket

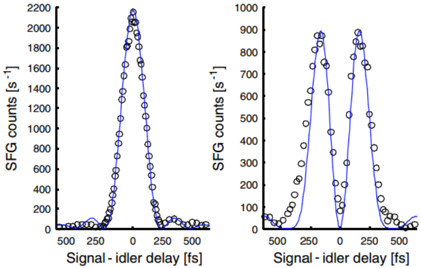
$$\psi(\tau) = \int_0^\infty d\Omega\, \phi(\Omega) H_s(\omega_0 + \Omega) H_i(\omega_0 - \Omega) e^{-i\Omega\tau}$$

Biphoton Pulse Shaping

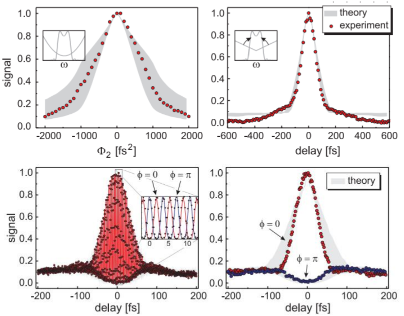
- Biphoton SFG permitted first demonstration of entangled-photon pulse shaping in 2005.



Phase Shaping



Phase and Amplitude Shaping

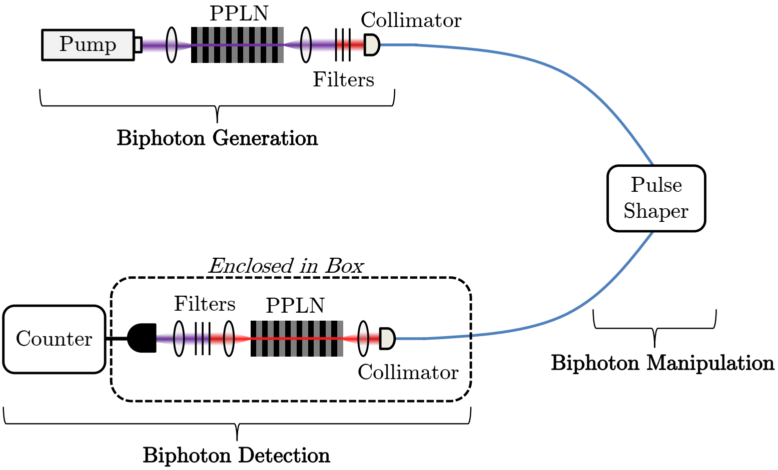


A. Pe'er *et al.*, Phys. Rev. Lett. **94**, 073601 (2005).

F. Zäh, M. Halder, and T. Feurer, Opt. Express **16**, 16452 (2008).

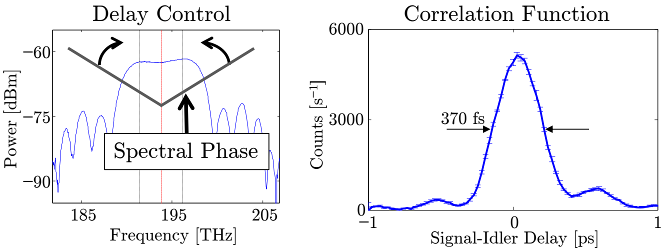
Our Experimental Setup

- Our goal is to use extremely efficient PPLN waveguides, coupled with high-resolution pulse shaping, to explore new regimes for spectral manipulation of entangled photons.



Implementing Ultrafast Coincidence Detection

- Pulse shaper can control signal-idler delay with linear spectral phase.
- PPLN waveguides offer ultrahigh conversion efficiency.



Conversion Efficiency

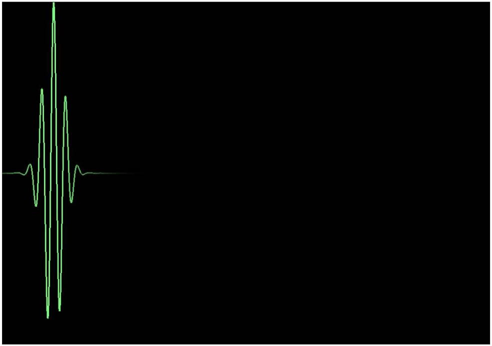
$$\eta_{\mathrm{SFG}} \approx 10^{-5}$$

100× higher than reported best.

J. M. Lukens *et al.*, Phys. Rev. Lett. **111**, 193603 (2013).

Optical Dispersion

- Frequency-dependent refractive index makes different wavelengths propagate at different speeds.
- Causes spreading of ultrafast pulses, but can in principle be compensated by a second medium with the opposite sign of dispersion.



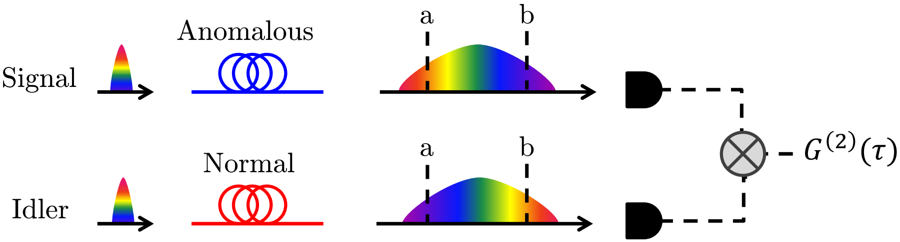
Animation by A. J. Metcalf (2013).

Nonlocal Dispersion Cancellation

- Biphoton correlations spread with dispersion as well, but entanglement allows this to be undone *nonlocally*.
- Taking $H_s(\omega) = \exp[i\Phi_s(\omega)]$ and $H_i(\omega) = \exp[i\Phi_i(\omega)]$, we note that $\psi(\tau)$ is unchanged whenever

Dispersion Cancellation Condition

$$\Phi_s(\omega_0 + \Omega) = -\Phi_i(\omega_0 - \Omega)$$

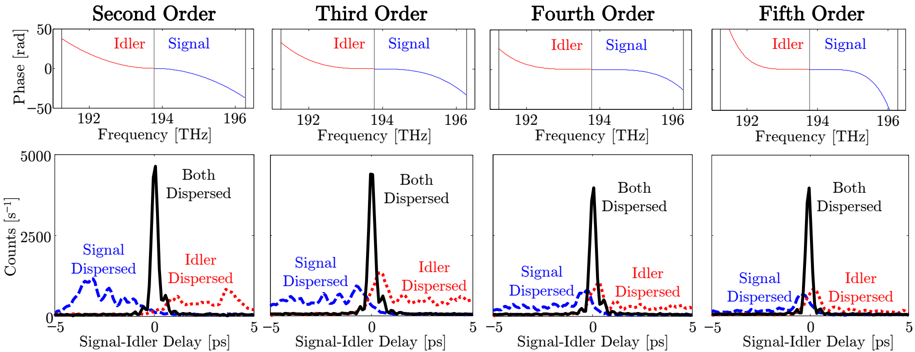


J. D. Franson, Phys. Rev. A **45**, 3126 (1992).

Our Experiments

- Control of arbitrary orders made possible by pulse shaper.
- For spectral phases $\Phi_{s,i}(\omega) = \sum_n \Phi_{s,i}^{(n)} (\omega - \omega_0)^n / n!$, we check the cancellation condition

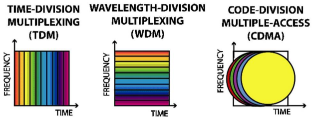
$$\Phi_s^{(n)} + (-1)^n \Phi_i^{(n)} = 0.$$

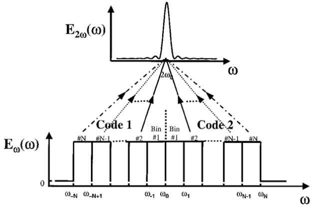


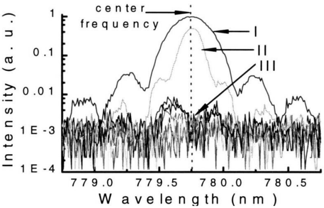
J. M. Lukens *et al.*, Phys. Rev. Lett. **111**, 193603 (2013).

Classical Spectral Coding

- Optical code-division multiple-access (O-CDMA) gives alternative to time-division and wavlength-divison multiplexing.
- One technique uses narrowband SFG to correlate codes on opposite halves of the spectrum.
- Mismatched codes are ideally orthogonal.





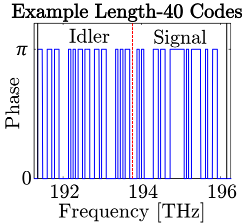


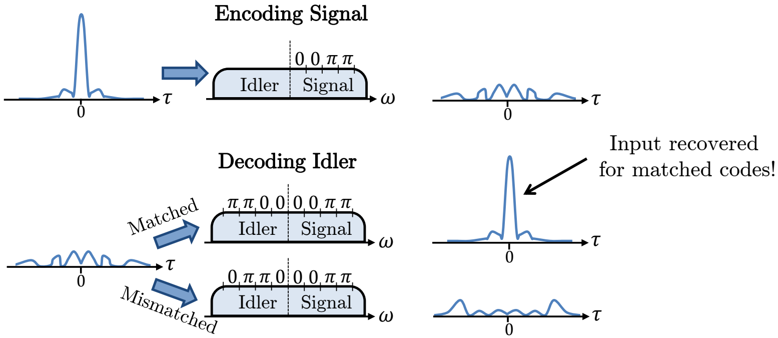
Z. Zheng and A. M. Weiner, Opt. Lett. **25**, 984 (2000).

A. M. Weiner, Z. Jiang, and D. E. Leaird, J. Opt. Netw. **6**, 728 (2007).

Extending to Biphotons

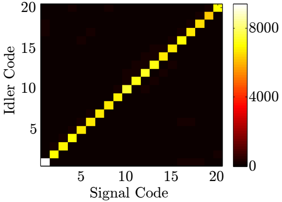
- Signal and idler correlations permit orthogonal spectral coding in which the signal is "encoded" and the idler "decoded."
- Can be nonlocal, unlike classical case.

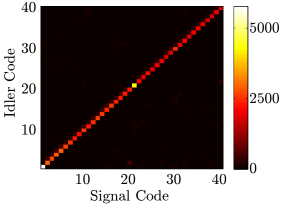


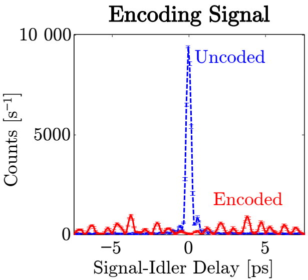


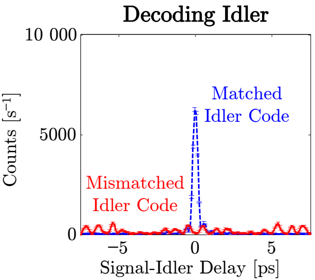
Experimental Results

- Coincidences at zero delay for length-20 and length-40 codes. →
- Full correlation functions for specific example. ↓







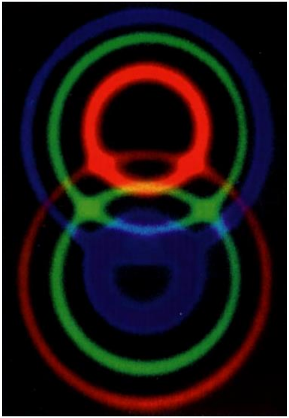


J. M. Lukens *et al.*, Phys. Rev. Lett. (in press).

Conclusion

- We have shown how the spectro-temporal properties of entangled photons can be controlled in novel ways with classical pulse shaping techniques.
- Results are of both fundamental and practical relevance.

1. High-order dispersion cancellation potentially useful for generating single-cycle biphotons.
2. Spectral coding could be developed into new high-dimensional QKD protocols based on time-frequency correlations.



A. Zeilinger, Rev. Mod. Phys. **71**, S288 (1999).