Control of Frequency Correlations of Two-Photon States in Parametric Downconversion

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OUTLINE

- Goal and motivation of the experiment
- How to generate different frequency correlations of entangled pairs of photons
- Experiment and experimental results

- The **goal** of the experiment:

  to generate
  – frequency-**correlated**
  – frequency-**anticorrelated**
  – frequency-**uncorrelated**
  pairs of entangled photons

- **Motivation**

  - Different applications require different correlations

    – correlations – enhanced time and position measurements; atomic clock synchronization

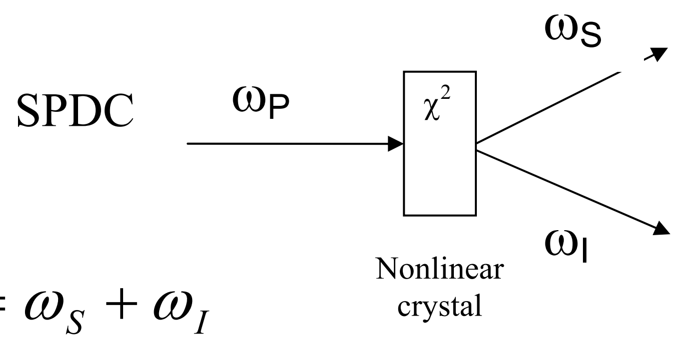
    – anticorrelations – quantum optical coherence tomography

    – no correlations – generation of multiparticle entanglement

  - Recovery of entanglement of photon pairs generated with a femtosecond pump

  - Multi-dimensional Hilbert space of continuous variables

1) Generation of **frequency anticorrelated** photon pairs



$$\omega_P = \omega_S + \omega_I$$

$$|\psi\rangle = \int d\Omega\, \Phi(\Omega)\, |\omega_P/2+\Omega\rangle_S |\omega_P/2-\Omega\rangle_I$$

- Possible with a CW pump with bandwidth $\Omega_P = 0$
- But, if $\Omega_P \neq 0$, the symmetries get broken and entanglement is lost

2) Generation of **frequency correlated** photon pairs

- $\Omega_P \neq 0 \quad \Rightarrow \quad |\psi\rangle = \int d\Omega\, \Phi(\Omega)\, |\omega_P/2+\Omega\rangle_S |\omega_P/2+\Omega\rangle_I$
- Possible with PP nonlinear crystals [PRL **94**, 083601 (2005)] at a specific wavelength, bandwidth, etc.
- Achromatic Phase Matching [PRA **71**, 022320 (2005)]

Parametric Downconversion

Energy conservation: $\omega_P = \omega_S + \omega_I$

Momentum conservation: $\vec{k}_P = \vec{k}_S + \vec{k}_I$

Phase Mismatch: $\Delta\vec{k} = \vec{k}_P - \vec{k}_S - \vec{k}_I$

If $\Omega_P \neq 0 \quad \Rightarrow \quad \Delta\vec{k} = 0$ for one wavelength only

Achromatic Phase Matching (APM)

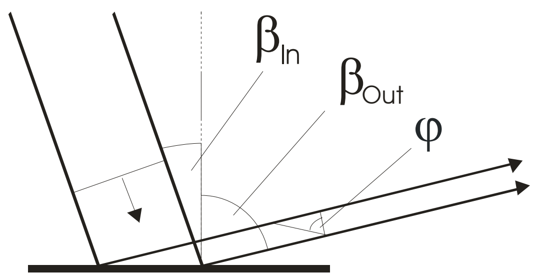
O.E. Martínez, *Achromatic Phase Matching for Second Harmonic Generation of Femtosecond Pulses, IEEE J. Quantum Electron.* ***25****, 2464 (1989)*

Introduces **angular dispersion** to guarantee **phase matching for all wavelengths** of the broad-bandwidth pump pulse in order to improve the efficiency of the SHG.

What happens to the entanglement if we use APM for downconversion?

J.P. Torres, M.W. Mitchell, and M. Hendrych, *Indistinguishability of Entangled Photons Generated with Achromatic Phase Matching*, Phys. Rev. A **71**, 022320 (2005)

E.g. a **diffraction grating**



$$k_x \Rightarrow k_x/\alpha - \Omega\tan\varphi/\alpha c$$

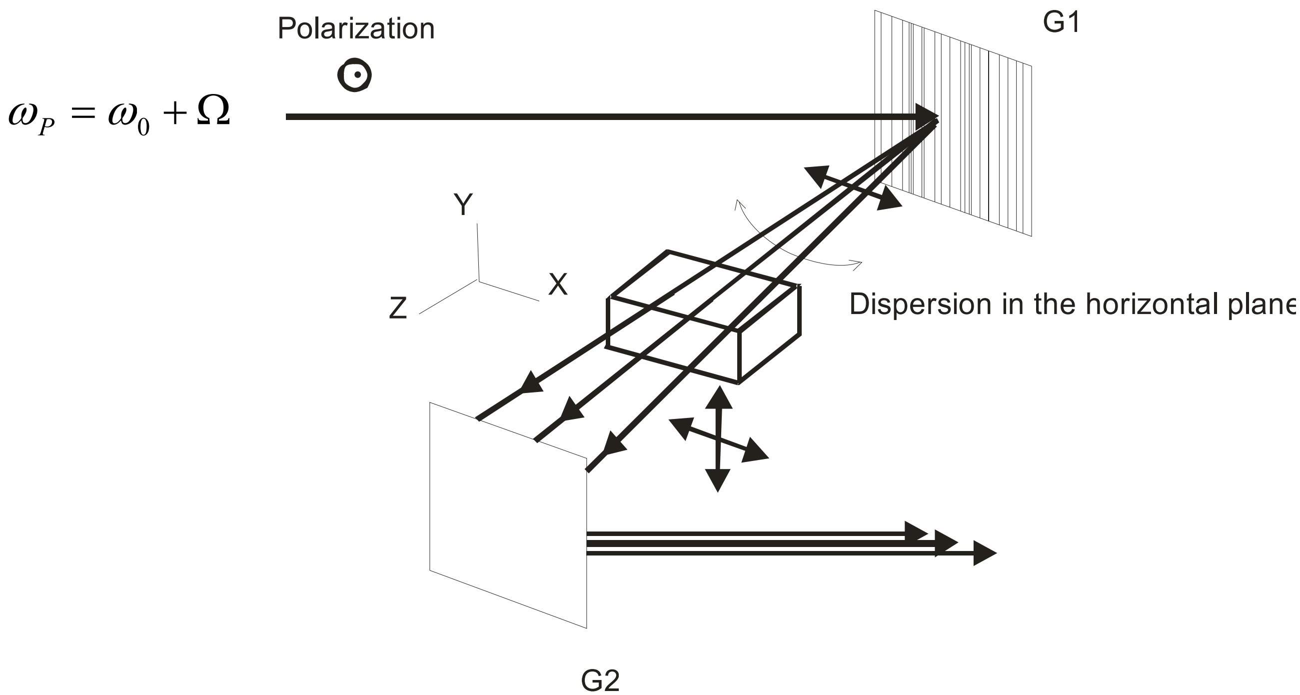
$$\tan\varphi = -\frac{n\lambda}{d\cos\beta_{out}}$$

k_x – transversal k-vector before the grating
Ω – bandwidth of the pump
φ – pulse-front tilt
c – speed of light
$\alpha = -\cos\beta_{in} / \cos\beta_{out}$

n – diffraction order
λ – wavelength
d – groove spacing of the grating
β_{out} – output diffraction angle

Collinear type-II SPDC in a uniaxial χ_2 crystal with the optic axis in the XZ plane so that the pump walk-off $\rho_P = (\rho_0, 0)$

E.g. BBO, $LiNbO_3$, etc.



Each wavelength propagates at its phase matching angle
and the inverse group velocities of the pump and signal beams N_p and N_s

$$N'_P = N_P + (\tan\varphi \tan\rho_0)/c \quad \text{and} \quad N'_s = N_s + (\tan\varphi \tan\rho_s)/c$$

The pump beam inside the crystal:

$$\mathbf{E}_P^+(\mathbf{x},z,t)=\int d\omega_P d\mathbf{p}\, E_0\left(\omega_P, p_x/\alpha-\Omega_P\tan\varphi/\alpha c, p_y\right)e^{ik_P z+i\mathbf{p}(\mathbf{x}+z\rho_P)-i\omega_P t},$$

$k_P(\omega_P,\mathbf{p})=\left[(\omega_P n_P/c)^2-|\mathbf{p}|^2\right]^{1/2}$ – longitudinal wave number

$\mathbf{p}$ – transversal wave number

The state of the photon pair at the output of the crystal:

$$|\psi\rangle=\int d\omega_s d\omega_i d\mathbf{p}d\mathbf{q}\, E(\omega_s,\omega_i,\mathbf{p},\mathbf{q})\,\mathrm{sinc}\left(\Delta k L/2\right)e^{i\Delta k L/2}\,\hat{a}_s^+(\omega_s,\mathbf{p})\hat{a}_i^+(\omega_i,\mathbf{q})|0,0\rangle,$$

with the phase mismatch

$$\begin{aligned}\Delta k &= k_p\left(\omega_s+\omega_i, \bar{p}_x+\bar{q}_x, p_y+q_y\right)+\left(\bar{p}_x+\bar{q}_x\right)\tan\rho_0\\ &\quad -k_s\left(\omega_s,\bar{p}_x,p_y\right)-\bar{p}_x\tan\rho_s-k_i\left(\omega_i,\bar{q}_x,q_y\right)\end{aligned}$$

where after the second grating

$\bar{p}_x=\alpha p_x+\Omega_s\tan\varphi/c$ and $\bar{q}_x=\alpha q_x+\Omega_i\tan\varphi/c$

$$k(\omega_0+\Omega)=k(\omega_0)+\frac{\partial k(\omega)}{\partial\omega}\Omega+\cdots$$

$$\boxed{\Delta k=0}$$ if $$\boxed{\frac{\Omega_i}{\Omega_s}=-\frac{N_P+\tan\varphi\tan\rho_0/c-N_s-\tan\varphi\tan\rho_s/c}{N_P+\tan\varphi\tan\rho_0/c-N_i}}$$

1) **Frequency anticorrelations**:

$$\frac{\Omega_i}{\Omega_s}=-1$$ when $$N_i-N_s=1/c\,\tan\varphi\,\tan\rho_s$$

2) **Frequency correlations**:

$$\frac{\Omega_i}{\Omega_s}=1$$ when $$N_P-1/2(N_i+N_s)=1/2c\,\tan\varphi\,(\tan\rho_s-2\tan\rho_0)$$

Experiment

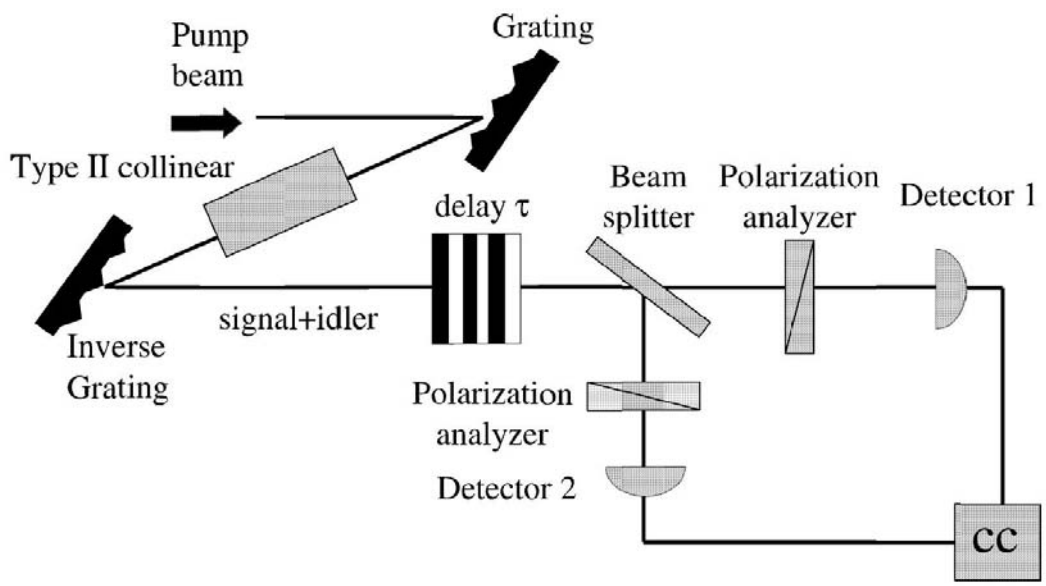


Fig. 1: Scheme of the experiment

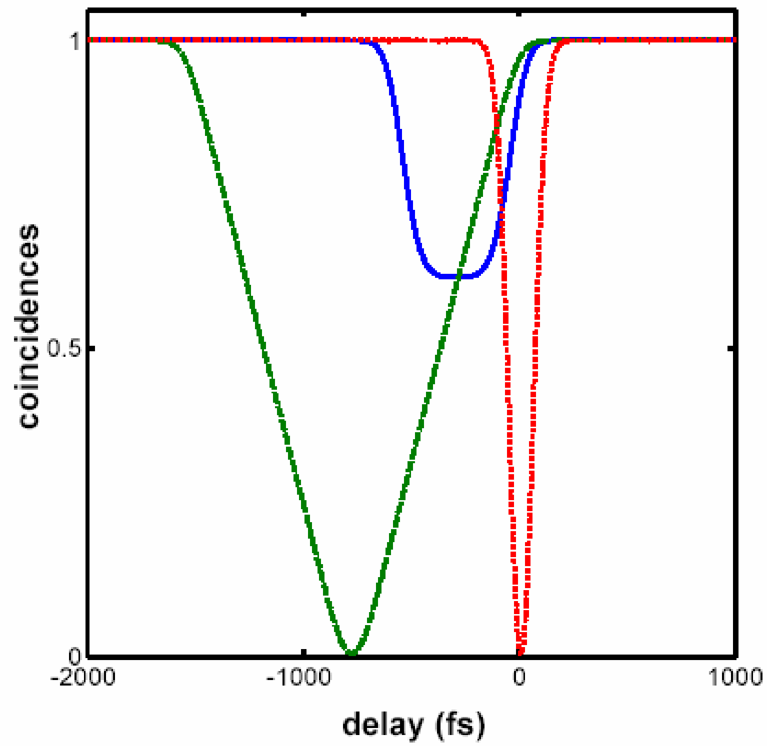


Fig. 2: HOM dips. Coincidence rate as a function of temporal delay τ for 3 different values of the tilt angle of the pump pulse.

Solid line: φ = *0°*

Dashed line: φ = *-53.1°* *frequency correlated photons*

Dotted line: φ = *39.6°* *frequency anticorrelated photons*

polarizers' angles $\phi_a = -\phi_b = 45^o$; crystal length L = *3* mm;

pump badwidth Ω_P ~ 4 nm; filter bandwidth $\Delta\lambda$ = *10* nm

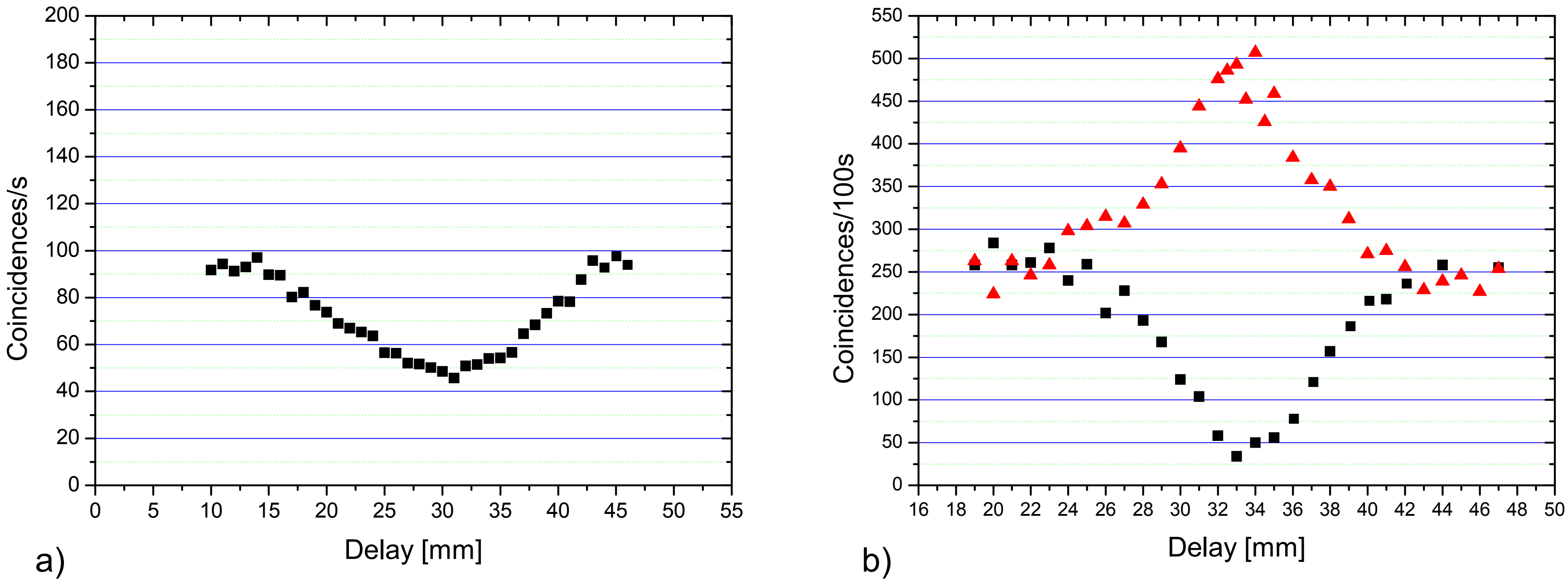


Fig. 3: Number of coincidences as a function of the temporal delay τ.

a) $\varphi = 0^o$, $\phi_a = -\phi_b = 45^o$, V = 32%

b) $\varphi = 39.6^o$, $\phi_a = -\phi_b = 45^o$ (-■-), $\phi_a = \phi_b = 45^o$ (-▲-), V = 88%

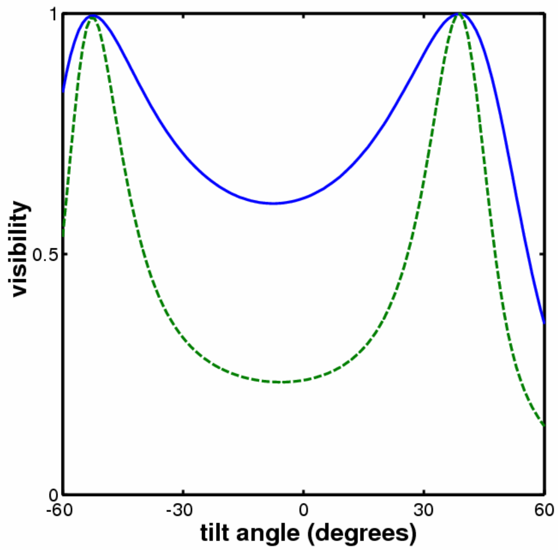


Fig. 4: Visibility of the HOM dip as a function of the pump-tilt angle.

Solid line: crystal length L = 1.5 mm
Dashed line: L = 3 mm

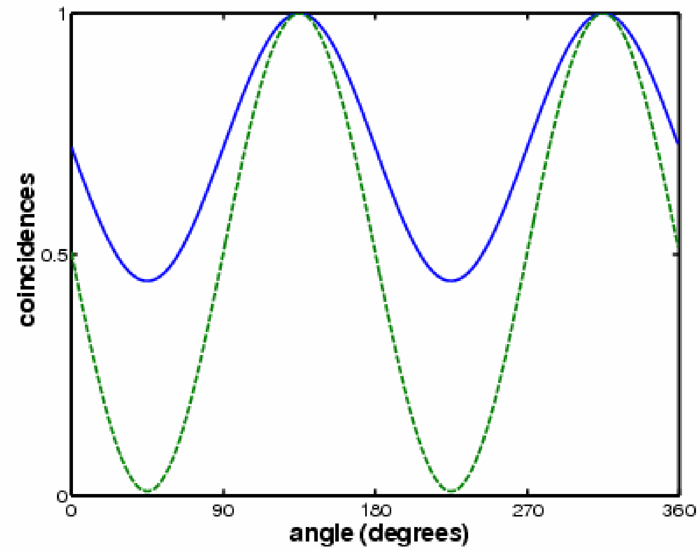


Fig. 5: Coincidence rate as a function of the polarization angle ϕ_b for fixed $\phi_a = -45^o$.

Solid line: φ = 0^o
Dashed line: φ = -53.1^o

CONCLUSIONS:

- Method to generate **entangled photons** with **femtosecond pulses**
- Tailoring frequency entanglement of photon pairs at will:
  - **frequency correlations**
  - **frequency anticorrelations**
  - **no correlations**
- Hilbert space of continuous variables
- No special crystals (PP) or spectral filtering necessary