Generation of indistinguishable and pure heralded single photons with tunable bandwidth

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We describe a new scheme to *fully* control the joint spectrum of paired photons generated in spontaneous parametric downconversion. We show the capability of this method to generate frequency-uncorrelated photon pairs that are pure and indistinguishable and whose bandwidth can be readily tuned. Importantly, the scheme we propose can be implemented in any nonlinear crystal and frequency band of interest. © 2008 Optical Society of America

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The generation of pure and indistinguishable single photons with a well-defined spatiotemporal mode is a fundamental requisite in many quantum optics applications [1]. For example, in the field of linear optical quantum computing (LOQC), the nonfulfillment of these requisites may degrade the quantum gate fidelity [2]. Various methods to generate single photons have been proposed and implemented [3]. One method is to combine spontaneous parametric downconversion (SPDC) with conditional measurements, where one of the paired photons is used as a trigger to herald the presence of the other photon [4]. However, owing to the entangled nature of the photons generated in the SPDC process, the resulting heralded single photons are not generally described by a pure quantum state, which severely limits the usefulness of such photons.

The quantum description of photons includes the polarization, the transverse wavenumber distribution, and the spectrum. When considering SPDC sources, indistinguishable paired photons in polarization can be obtained with a type I configuration. In the spatial domain, pure states can be obtained, for instance, by collecting the downconverted photons with a pair of single-mode optical fibers.

Regarding the frequency, pure heralded photons can be generated if strong spectral filtering is used in the path of the trigger photon. However, the use of spectral filters represents a considerable drawback, as it results in a loss of the source brightness, unless the SPDC configuration already generates narrowband photons, as in the case of cavity SPDC [5,6].

Another way to generate pure heralded photons is to produce frequency-uncorrelated photons. It has been demonstrated that frequency-uncorrelated photons generated by SPDC are indeed in a pure state [7]. Frequency-uncorrelated photons can be produced in special crystals with suitable pump-light conditions and specific values of the length and dispersive properties of the nonlinear crystals [8]. Unfortunately, with this approach the produced photons are not indistinguishable, and one is limited in using specific materials and wavelengths that can be far from optimal. Various techniques have been proposed to control the joint spectrum of SPDC pairs. Some methods are based on the proper preparation of the downconverting crystal [9]; others are based on the use of angular dispersion to control the dispersive properties of interacting waves [10] and noncollinear geometries [11,12].

In this Letter, we propose what we believe is a new method for tailoring the frequency properties of SPDC photons that avoids the use of strong filtering to obtain pure heralded single photons. In addition, the technique allows us to tune the frequency bandwidth of the generated single photons. This might benefit various applications, i.e., atom–photon interactions require light with a narrow bandwidth (~MHz), while quantum coherence tomography [13] and certain quantum information processing applications [14] require large bandwidths (~THz). Importantly, the proposed technique enables one to obtain any kind of frequency correlation between the paired photons (anticorrelation, uncorrelation, or correlation). Compared to other methods this approach works at any wavelength and for any nonlinear medium.

The method is based on the fact that the joint spectrum of paired photons can be independently modified by (a) using noncollinear geometries that allow mapping the spatial characteristics of the pump beam into the spectra (spatial-to-spectral mapping) [15] and (b) introducing angular dispersion to modify the group velocities of the interacting fields (pulse-front-tilt technique) [16].

The scheme is illustrated in Fig. 1. A noncollinear degenerate type I SPDC configuration is used. However, unlike the standard SPDC, angular dispersion

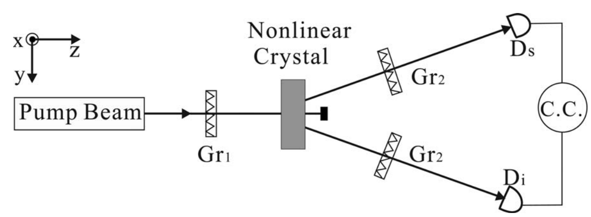

Fig. 1. General scheme. Gr_1 and Gr_2, gratings; D_s and D_i, single-photon counting modules; C.C., coincidence counter.

is applied to the pump beam and downconverted photons. A diffraction grating or prism introduces angular dispersion ϵ that tilts the front of the pulse by an angle ξ given by $\tan\xi=-\lambda\epsilon$, where $\epsilon=m/(d\cos\beta_0)$, m is the diffraction order, d is the groove spacing, β_0 is the output diffraction angle, and λ is the wavelength.

The generated signal and idler photons at wavelengths λ_s and λ_i propagate inside the crystal in the y–z plane at an angle $\varphi_s=-\varphi_i=\varphi$ with respect to the direction of propagation of the pump beam. In contrast, the angular dispersion is introduced in the orthogonal z–x plane. The diffraction gratings Gr_2 in the downconverted beams compensate for the dispersion introduced by the grating Gr_1 in the pump beam with angular dispersion $\epsilon'=-\epsilon$.

The quantum state of the SPDC photons writes $|\Psi\rangle=\int d\omega_s d\omega_i \Phi(\omega_s,\omega_i)|\omega_s\rangle|\omega_i\rangle$, where ω_j is the angular frequency and the subscript j stands for signal (s), idler (i), and pump (p). The two-photon probability amplitude or biphoton can be written as

$$\Phi(\omega_s,\omega_i) \propto E_\omega(\omega_s+\omega_i)E_q[(k_s-k_i)\sin\varphi] \times \operatorname{sinc}\left(\frac{\Delta kL}{2}\right)\exp\left\{i\frac{\Delta kL}{2}\right\}, \quad (1)$$

where E_ω is the pump spectrum, E_q is the pump transverse momentum distribution along the y direction, and $\operatorname{sinc}(\Delta kL/2)$ is the phase-matching function. $\Delta k=k_p-(k_s+k_i)\cos\varphi$ is the phase mismatch in the longitudinal direction.

Let us write $\lambda_j=\lambda_j^0+\Lambda_j$, where Λ_j is the wavelength detuning from the central wavelength λ_j^0. Furthermore, let us define new variables $\Lambda_+=(\Lambda_s+\Lambda_i)/\sqrt{2}$ and $\Lambda_-=(\Lambda_s-\Lambda_i)/\sqrt{2}$ associated with the diagonal (straight line with a slope of 45°) and the antidiagonal (straight line with a slope of −45°) of a two-dimensional density plot of the joint spectrum $S(\lambda_s,\lambda_i)=|\Phi(\lambda_s,\lambda_i)|^2$, which is the probability of measuring a signal photon with wavelength λ_s in coincidence with an idler photon with λ_i.

The pump spectrum and transverse-momentum amplitude distributions are assumed to be Gaussian, i.e., $E_\omega(\omega_p)\propto\exp[-\omega_p^2/(4B_p^2)]$ and $E_q(\vec{q}_p)\propto\exp[-|\vec{q}_p|^2W_0^2/4]$, where B_p is the frequency bandwidth of the pump, W_0 is the pump beam waist, and $\vec{q}_p=(q_x,q_y)$ is the transverse wave vector. Furthermore, we approximate the phase-matching function $\operatorname{sinc}(\Delta kL/2)$ by an exponential function of the same width at $1/e$ of the amplitude, $\operatorname{sinc}(bx)\simeq\exp[-(\alpha b)^2x^2]$ with $\alpha=0.455$. If we project the signal and idler photons into large-area spatial modes to the first order in all frequency variables, the joint spectrum reduces to

$$S(\Lambda_s,\Lambda_i)=\mathcal{N}\exp\left\{-\frac{\Lambda_+^2}{2\Delta\Lambda_+^2}\right\}\exp\left\{-\frac{\Lambda_-^2}{2\Delta\Lambda_-^2}\right\}, \quad (2)$$

where $\mathcal{N}$ is a normalization factor and $\Delta\Lambda_+$ and $\Delta\Lambda_-$ are the rms bandwidths of the variables Λ_+ and Λ_-, respectively, given by

$$\Delta\Lambda_+=\frac{\lambda_s^2}{2\pi c}\frac{1}{\sqrt{2}}\left[\frac{1}{B_p^2}+(\alpha L)^2(N_p'-N_s\cos\varphi)^2\right]^{-1/2}, \quad (3)$$

$$\Delta\Lambda_-=\frac{\lambda_s^2}{2\pi c}\frac{1}{\sqrt{2}}[N_s\sin\varphi W_0]^{-1}. \quad (4)$$

$N_j=dk_j/dw_j$ are the inverse group velocities, and $N_p'=N_p+\tan\rho_p\tan\xi/c$ is the effective inverse group velocity of the pump beam that depends on the Poynting-vector walk-off angle ρ_p and pulse-front-tilt angle ξ; c is the speed of light. In all calculations, we consider typical material parameters corresponding to commonly used nonlinear crystals, such as β-barium borate (BBO).

Equations (2)–(4) reveal the physics behind the proposed technique; once the pump bandwidth is fixed, the bandwidth in the Λ_+ direction can be modified by the pulse-front tilt [see Fig. 2(a)] and the bandwidth in the Λ_- direction by the size of the pump beam waist [see Fig. 2(b)]. Equation (3) shows that in the absence of tilt the maximum value of $\Delta\Lambda_+$ is determined by the dispersive properties of the material, the length of the crystal, and the noncollinear angle. However, if angular dispersion is introduced, the phase-matching function is modified, which allows us to reach the maximum value $\Delta\Lambda_+^{(\max)}=2\sqrt{2}\Delta\lambda_p$. This value is achieved by applying a tilt angle

$$\xi_0=\tan^{-1}\left\{\frac{c(N_s\cos\varphi-N_p)}{\tan\rho_p}\right\}. \quad (5)$$

The bandwidth in the Λ_- direction $\Delta\Lambda_-$ can be tailored by changing the pump beam waist at the input face of the nonlinear crystal in the y direction, W_0. This is due to the so-called spatial-to-spectral mapping that occurs when SPDC is used in noncollinear geometries [12,15]. In this configuration, the phase-matching conditions inside the nonlinear crystal enable the mapping of the spatial features of the pump beam in the y-direction into the joint spectrum of the downconverted photons along the Λ_- direction.

Figure 3 shows the joint spectrum for various combinations of the pulse tilt and beam waist. Each row corresponds to a different value of the tilt angle. The

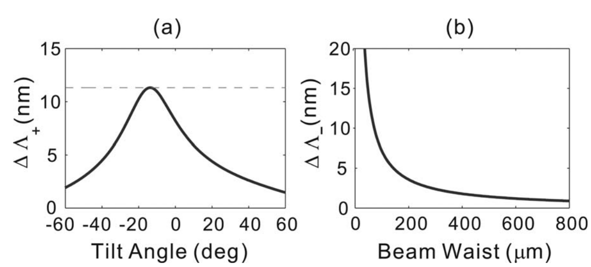

Fig. 2. Bandwidth of the joint spectrum: (a) $\Delta\Lambda_+$ as a function of the pulse-front-tilt-angle ξ. The dashed line indicates $\Delta\Lambda_+^{(\max)}$; (b) $\Delta\Lambda_-$ as a function of the pump beam waist in the y direction, W_0. Pump beam bandwidth, $\Delta\lambda_p=4$ nm.

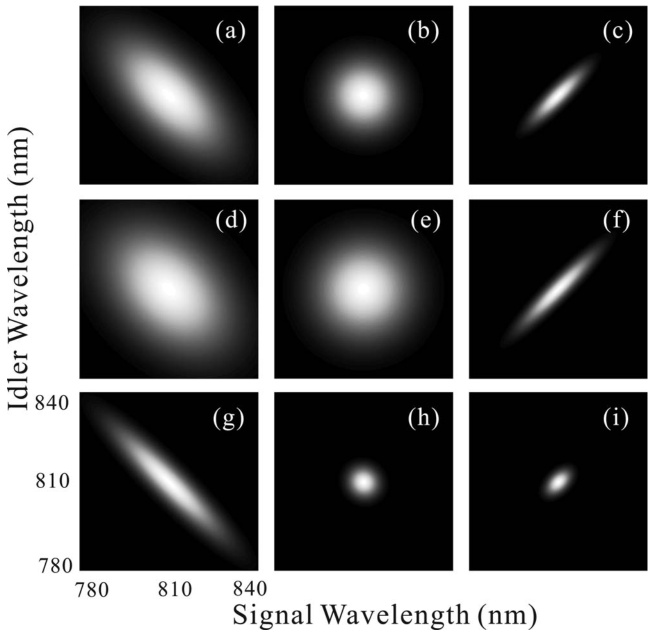

Fig. 3. Joint spectrum of the two-photon state for different values of the pulse-front tilt (ξ) and the beam waist (W_0): (a) $\xi=0°$, $W_0=30\ \mu$m; (b) $\xi=0°$, $W_0=60\ \mu$m; (c) $\xi=0°$, $W_0=250\ \mu$m; (d) $\xi=\xi_0=-13.8°$, $W_0=30\ \mu$m; (e) $\xi=\xi_0=-13.8°$, $W_0=45\ \mu$m; (f) $\xi=\xi_0=-13.8°$, $W_0=250\ \mu$m; (g) $\xi=30°$, $W_0=30\ \mu$m; (h) $\xi=30°$, $W_0=140\ \mu$m; (i) $\xi=30°$, $W_0=250\ \mu$m. The circular shape of the distributions shown in the central column indicates frequency uncorrelation between the photons with a different bandwidth.

first row depicts the case with no tilt ($\xi=0°$); the second row corresponds to $\xi=\xi_0=-13.8°$, which yields the maximum bandwidth in the $\Delta\Lambda_+$ direction that can be obtained for a given pump bandwidth; and the third row corresponds to $\xi=30°$. When the bandwidths in the Λ_+ and Λ_- directions are equal, indistinguishable and frequency-uncorrelated photons are generated. This can be achieved by choosing an appropriate combination of the tilt and beam waist as depicted in the central column of Fig. 3. It can easily be seen how the frequency bandwidth of single photons can be tuned by modifying the tilt and beam waist.

Figure 3 also reveals that the setup discussed for the generation of pure heralded photons allows the production of paired photons with different types of frequency correlations. As a matter of fact, frequency uncorrelation is just a particular case. The first and third columns of Fig. 3 correspond to different values of the pump beam waist in the y direction, $W_0=30$ and $W_0=250\ \mu$m, respectively. The first column depicts highly frequency-anticorrelated photons, while the third column illustrates the case of highly frequency-correlated photons.

In conclusion, a new technique for the generation of heralded indistinguishable and pure single photons with a tunable frequency bandwidth has been presented. The full control of the joint spectrum allows us to generate frequency-correlated and frequency-anticorrelated photon pairs as well. The proposed method combines SPDC in noncollinear geometries with the use of pulse-front tilt. The control parameters used to tune the frequency characteristics are readily experimentally accessible: pump beam width and angular dispersion. The method described here works in any frequency band of interest and does not require any specific engineering of the dispersive and nonlinear properties of the nonlinear medium.

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