Frequency-to-time Mapping-Assisted Spectral Characterization of Parametric Biphoton States

Anahita Khodadad Kashi[1,2], Benjamin Wetzel[3], and Michael Kues[1,2]
[1]*Institute of Photonics, Leibniz University Hannover, Nienburger Str. 17, 30167 Hannover, Germany*
[2]*Cluster of Excellence PhoenixD, Leibniz University Hannover, Hannover, Germany*
[3]*XLIM Research Institute, CNRS UMR 7252, Université de Limoges, Limoges 87060, France*
anahita.khodadadkashi@iop.uni-hannover.de, michael.kues@iop.uni-hannover.de

Abstract: Frequency-to-time mapping technique is employed to directly characterize the biphoton state from a pulsed spontaneous parametric process. For the first time Hanbury Brown and Twiss measurement is performed directly in the frequency domain.

The spectral characterization of biphoton states emitted from spontaneous parametric processes is crucial to implement quantum information processing tasks that often require tailor-made frequency correlations to obtain for example, quantum interference of high visibility [1]. To date the demonstrated characterization techniques have been primarily based on long-time successive frequency scanning over the biphoton-state spectrum. Spectral filtering of photon pairs renders inefficient detection rates which adversely affects the signal-to-noise ratio (SNR) and in turn restricts the accessible spectral resolution. In addition, the limited frequency-bandwidth of the filtration devices further constraints the accessible spectral resolution of such characterization technique. Other measurement schemes based on frequency-to-position mapping [3] and Fourier spectroscopy suffer from low spectral resolution, instability and long integration times [4]. In stimulated parametric emission characterization schemes, despite fast implementation owing to high optical powers, the stimulated emission itself becomes a source of noise which degrades the SNR [5].

In this paper we demonstrate a novel and time-efficient technique to directly characterize, through a single coincidence measurement, the spectral correlations of a biphoton state from a pulsed-driven SPDC process. For this, the well-established technique of frequency-to-time mapping (FTM) was employed which relies on chromatic dispersion to image the frequency components of a biphoton-state spectrum onto a time-stretched temporal waveform. Specifically, in this work we exploited the time-resolved coincidence detections to reconstruct the biphoton joint spectral intensity (JSI). Importantly, this technique allowed us to demonstrate for the first time a frequency resolved Hanbury-Brown and Twiss measurement. Particularly, we directly measured the dependency of the second-order auto-correlation function $g^{(2)}(\Delta\upsilon)$ on the spectral difference $\Delta\upsilon$ of the involved photons, directly revealing the single frequency mode bandwidth. This is in contrast to the common demonstrations of $g^{(2)}(\tau)$ as function of delay τ between the photons.

The experimental setup (see Figure. 1. a) consisted of a periodically-poled lithium niobate (PPLN) waveguide excited by a pulsed mode-locked laser which was filtered to a full-width at half-maximum (FWHM) of δ_{pump}= 200 GHz at the center wavelength of λ_{pump}= 778.8 nm. Out of type-0 SPDC processes, highly time-frequency correlated photon pairs were generated within the PPLN waveguide. A dispersion compensating fiber (DCF) with a dispersion factor of D = 960 ps/nm, allowed for the formation of a temporally-resolved replica of the SPDC biphoton spectrum, to be detected with single photon detectors (time resolution t_r ~ 25 ps). With the use of a programmable filter, an 800 GHz spectral bandwidth was carved out symmetric to the SPDC degeneracy point (see Figure 1. b inset). The signal (idler) field, was half-split and directed towards our superconducting nanowire single photon detectors (SNSPD) D1 and D2 (D3 and D4). A start-stop timing electronics unit, with its operation synchronized to our pulsed-laser repetition rate (50 MHz), recorded the coincidence detections. The time-resolved coincidence detections of the signal and idler spectrum with $\Delta\upsilon$ = 400 GHz bandwidth, were registered over the pulse period of 20 ns (See Figure 1. b). By relating the temporal width $\Delta T_{scaled} \approx 3300$ ps of the time-scaled intensity profile, to the initial undispersed spectral bandwidth, $\Delta\upsilon$ = 400 GHz, the frequency-to-time correspondence was revealed: $C_{FTM} = 0.1212$ GHz/ps. Considering the detector time resolution, the frequency resolution of the whole system reads υ_r ~ 3.03 GHz.

The recorded coincidence detections on D1 and D2 were used to directly perform the Hanbury Brown and Twiss measurement in the frequency domain; The temporally-resolved coincidence detections from the signal field enabled us to directly probe into the spectral dependency of the $g^{(2)}(\Delta\upsilon)$ function via a single two-fold coincidence measurement over the $\Delta\upsilon$ = 400 GHz bandwidth of the signal field. Figure 2. a illustrates the total intra- and inter-pulse coincidence counts as function of the frequency difference between the signal photons. At around zero-frequency difference and for the case of intra-pulse events – i.e. coincidence detections occurring within one pulse period – peak coincidence counts are observed, whose ratio to the number of inter-pulse events – i.e. coincident detections between different pulses – was measured to be $g^{(2)}(0) = 2$ (see the inset to the Figure 2. a). The FWHM of this spectral range allows the direct determination of the single frequency-mode bandwidth of our system to $\delta_{SMB} \sim 57.18$ GHz. This was verified by comparison with the conventional measurement of the $g^{(2)}$ function dependent on the spectral filter-bandwidth. In Figure 2. b, the coincidence to accidental ratio and the JSI of the signal and idler fields are illustrated as function of their symmetric positive and negative frequency offset from the degeneracy point, respectively. The ratio between the signal-idler actual (intra-) and accidental (inter-pulse) coincidence counts was calculated: CAR≈ 80 (See inset in Figure 5. (b)).

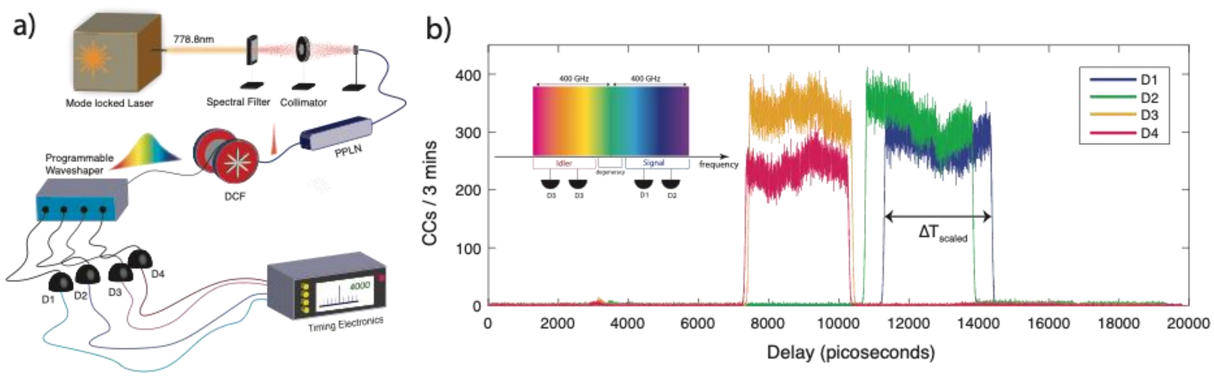

Figure 1. a) Experimental setup. **b)** Time-stretched replica of the signal and idler spectrum. (See text for more details)

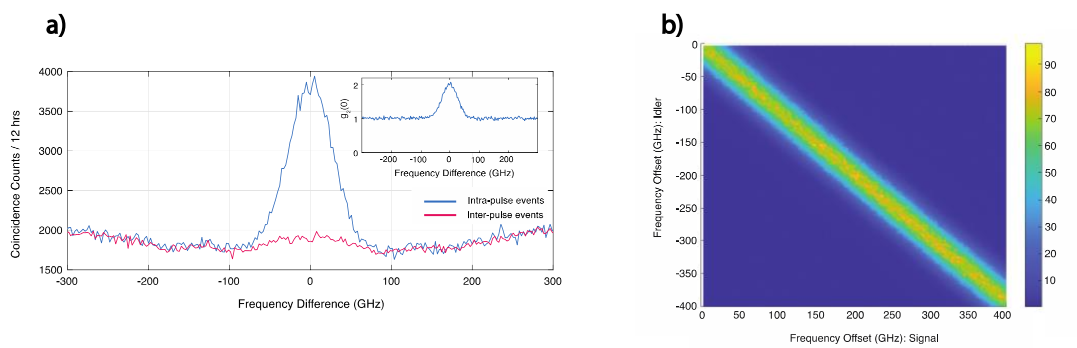

Figure 2. a) Second-order auto-correlation function of the signal field, as function of frequency difference between the spectral components. **b)** Joint spectral intensity (JSI) and the CAR versus the signal and idler frequency offset from the SPDC degeneracy point.

In summary, via a single coincidence measurement, a spontaneous parametric down-conversion process was characterized directly and time-efficiently, thanks to the FTM technique, whereby the frequency components of the SPDC output spectrum were resolved in time and their coincident detections were collected by exploiting the time synchronization provided by the pulsed excitation. For the first time we were able to demonstrate a direct measurement of the single frequency-mode bandwidth of the system by performing a spectral Hanbury Brown and Twiss measurement.

References

1. C. Joshi, A. Farsi, A. Dutt, B. Y. Kim, X. Ji, Y. Zhao, A. M. Bishop, M. Lipson, and A. L. Gaeta, "Frequency-Domain Quantum Interference with Correlated Photons from an Integrated Microresonator," Phys. Rev. Lett. **124**, 143601 (2020).
2. A. E. Ulanov, I. A. Fedorov, D. Sychev, P. Grangier, and A. I. Lvovsky, "Loss-tolerant state engineering for quantum-enhanced metrology via the reverse Hong-Ou-Mandel effect," Nat. Commun. **7**, 1–6 (2016).
3. K. D. Johnsen, P. Kolenderski, C. Scarcella, M. Thibault, A. Tosi, and T. Jennewein, "Time and spectrum-resolving multiphoton correlator for 300-900nm," J. Appl. Phys. **116**, (2014).
4. W. Wasilewski, P. Wasylczyk, P. Kolenderski, K. Banaszek, and C. Radzewicz, "Joint spectrum of photon pairs measured by coincidence Fourier spectroscopy," Opt. Lett. **31**, 1130 (2006).
5. F. Kaneda, J. Oikawa, M. Yabuno, F. China, S. Miki, H. Terai, Y. Mitsumori, and K. Edamatsu, "Spectral characterization of photon-pair sources via classical sum-frequency generation," Opt. Express **28**, 38993 (2020).