

Shaping of Time-Resolved Biphoton Correlations with a Microresonator-Based Spectral Shaper

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Abstract: We report on the manipulation of the time-resolved biphoton correlation function using a sub-GHz resolution silicon nitride microresonator-based spectral shaper capable of programmable amplitude and phase modulation.

Biphoton frequency combs (BFCs) are an attractive resource for quantum information processing because of their high dimensionality for encoding quantum information in the frequency domain and compatibility with fiber optics [1]. One way of obtaining phase-coherent BFCs is by spectrally filtering the broadband biphoton spectrum produced in a nonlinear waveguide [e.g. through spontaneous parametric downconversion (SPDC) in a periodically-poled lithium niobate waveguide (PPLN)]. The temporal correlation between photon pairs reveals the phase coherence of a BFC, resulting in time-resolved features at a period inverse of the frequency bin spacing under an envelope related to the bin width [2]. Likewise, by encoding phase information onto the frequency bins, the biphoton temporal correlation can be manipulated. There have been numerous works implementing amplitude and (or) phase spectral filtering of such broadband biphotons to manipulate the time-correlation functions [3]. However, spectral filtering that is typically achieved by a commercial bulk-optics-based waveshaper imposes a limitation on the resolution of > 10 GHz. This fundamentally leads to temporal features < 100 ps, reaching the timing resolution limit of commercially available superconducting nanowire single photon detectors (SNSPDs) and necessitating nonlinear [4] or electro-optic methods [5] to resolve the time-correlations. Integrated spectral shapers relying on fine-resolution microresonators [6,7] offer an interesting opportunity for manipulating the time-

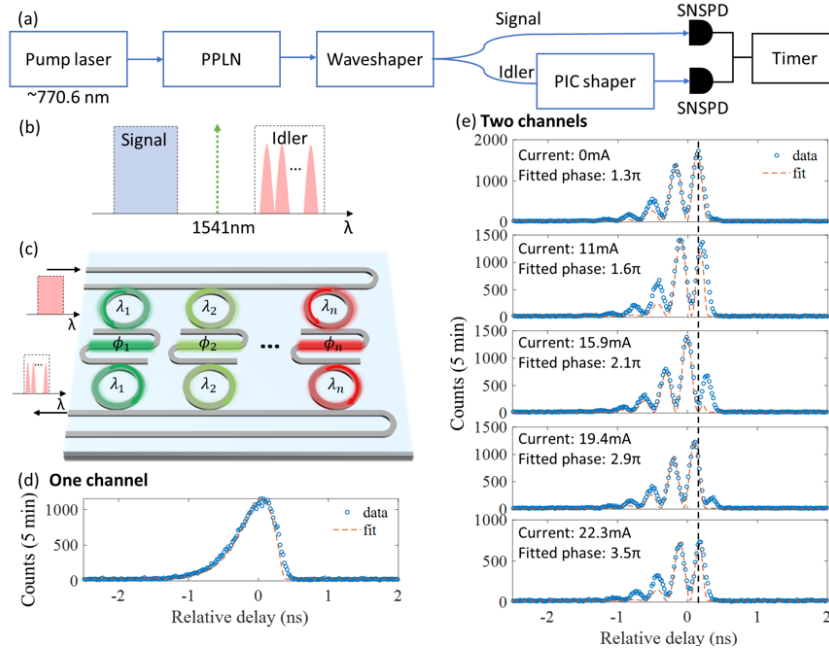


Fig. 1: (a) Diagram of the experimental setup. (b) Illustration of the biphoton spectrum carved by both the waveshaper (black dashed boxes) and on-chip shaper (red bins). The green dashed arrow indicates double the pump wavelength. (c) Schematic of the multi-channel spectral shaper chip. Coincidence histogram (blue circles) and a theoretical fit (orange dashed line) for (d) one shaper channel carving one idler bin, and (e) two shaper channels carving two idler bins. In (e), a varying spectral phase is applied to one of the shaper channels by incrementing the current provided to the phase shifter ϕ in the diagram of (c).

correlation function of biphotons. In particular, microresonators can be designed to achieve high quality factor, they are tunable via the thermo-optic effect, and they have a compact form factor. This could enable tunable fine-resolution amplitude and phase filtering functions to be applied across the biphoton spectrum in a scalable manner. In this paper, we develop a low-loss fine-resolution microresonator-based spectral shaper on a foundry Si_3N_4 platform. We use our system to carve two lines at a 3 GHz spacing from a broadband biphoton spectrum, and vary the relative phase between the lines to study the time-resolved biphoton correlation. By virtue of the fine spectral control, our on-chip shaper enables the manipulation of narrowly spaced frequency-bin states and facilitates direct observation of temporal correlation function with SNSPDs.

A schematic of our multi-channel microresonator-based spectral shaper is shown in Fig. 1(c). The top array of microresonators acts to download portions of a broadband input spectrum, route them through unique phase shifters, and then upload them onto a common output via a second identical microresonator. As a proof-of-concept demonstration, here we program only the first and the second channel of a six-channel device. The Si_3N_4 chip is fabricated by LIGENTECH on their 800 nm-thick AN-800 platform. Resonators are designed beyond the single-mode regime with a $15\text{-}\mu\text{m}$ waveguide width to reduce propagation loss and achieve finer spectral resolution. Euler curves within the resonators and phase-matched single-mode access waveguides keep the resonators operating predominately in the fundamental transverse electric (TE) mode. A shaper channel (two resonators tuned to a common mode, henceforth termed a *bin*) has a linewidth of ~ 600 MHz with an insertion loss that can be < 2 dB and a free spectral range (FSR) ~ 125 GHz. The Si_3N_4 platform has a dual-layer metallization with a high-resistivity metal layer used for thermo-optic phase shifting of the shaper elements. An optical fiber array and multi-contact wedge electrical probes are used to interface with the chip.

Our fine-resolution spectral shaper provides an excellent tool to investigate time-resolved biphoton cross-correlation. The experimental setup is depicted in Fig. 1(a). A continuous broadband biphoton spectrum is generated (centered near 1541 nm) via SPDC in a PPLN waveguide pumped by a tunable continuous-wave laser emitting at 770.6 nm. A fiber-coupled Waveshaper (Finisar) is then used to carve ~ 25 GHz wide portions of the signal and idler spectra (boxed outlines in Fig. 1(b)) and route them to separate optical fibers. The idler portion is additionally routed through the Si_3N_4 shaper for fine-resolution spectral carving and phase shifting (Fig. 1(c)). Finally, the carved signal and idler photons are sent to SNSPDs for coincidence measurement. The SNSPDs used in our experiments have a ~ 50 ps jitter. Our method for programming the shaper is described in-depth elsewhere [8]. First, we program the shaper to carve a single bin within the idler spectrum. The resulting biphoton temporal correlation function $|\psi(\tau)|^2$ is shown in Fig. 1(d). Further, to manipulate the time-resolved $|\psi(\tau)|^2$ using our fine-resolution shaper, we program it to carve two spectral bins at a 3 GHz spacing and vary the applied phase onto one of the bins. The results are shown in Fig. 1(e). Two bins carved in the idler spectrum results in the addition of oscillations to $|\psi(\tau)|^2$, periodic at the inverse bin spacing ($1/3\text{ GHz} \sim 333$ ps), within the overall envelope defined by the carved idler bin and signal transfer function. Moreover, applying a phase difference between the bins on the idler side results in a delay of the oscillations within the envelope. In the results of Fig. 1(e), we apply varying amounts of current to the phase shifter belonging to one of the two shaper bins and record the coincidence histograms over 5 minutes with a 20 ps histogram bin width. Each plot includes a best fit trace to the theoretical model, from which we extract the applied phases shown in the insets. As the top plot in Fig. 1(e) indicates, the phase difference between the two bins is non-zero even when no current is applied onto either bins. We see that by applying ~ 22 mA to the phase shifter corresponding to one of the bins, a $\sim 2\pi$ phase shift is achieved.

In conclusion, in this work we demonstrate the utility of a fine-resolution spectral shaper for manipulating the time-correlation function of photon pairs carved from a continuous biphoton spectrum. We show the fine spectral resolution of our on-chip shaper allows creation and line-by-line control of narrowly spaced frequency-bin entangled states that are unattainable with commercial pulse shapers. Our Si_3N_4 spectral shaper provides a low-loss and low-SWaP platform to enable future demonstrations of similar fully-integrated systems.

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References

1. H. H. Lu, *et al.* Nat. Commun. **13**, 4338 (2022).
2. P. Imany, *et al.*, Phys. Rev. A **97**, 013813 (2018).
3. A. Pe'er, *et al.*, Phys. Rev. Lett. **94**, 073601 (2005).
4. J.-P. W. MacLean, *et al.* Phys. Rev. Lett. **120**, 053601 (2018).
5. K. V. Myilswamy *et al.*, Physical Review Applied **19**, 034019 (2023).
6. A. Agarwal, *et al.*, J. Light. Technol. **24**(1), 77-87 (2006).
7. J. Wang, *et al.*, Nat. Commun. **6**, 5957 (2015).
8. L. M. Cohen, *et al.*, submitted to IEEE Silicon Photonics Conference 2024.