

On-chip pulse shaping of entangled photons

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The miniaturization of optical systems via integrated photonics is critical to the ultimate scalability and performance of photonic quantum processors, yet many longstanding optical signal processing capabilities—such as Fourier-transform pulse shaping—remain unrealized on chip. In this work, we demonstrate on-chip spectral shaping of entangled photons using a multichannel microring-resonator-based silicon photonic pulse shaper. Achieving line-by-line phase control on a 3 GHz grid for two frequency-bin-entangled qudits, the pulse shaper's fine spectral resolution enables control of nanosecond-scale temporal features, which are observed by direct coincidence detection of biphoton correlation functions that show excellent agreement with theory. This work marks a demonstration of biphoton pulse shaping using an integrated spectral shaper and holds significant promise for applications in photonic quantum information processing.

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I. INTRODUCTION

Entanglement serves as a pivotal resource in quantum information processing (QIP) [1–3], quantum communication [4–7], and quantum networking systems [8,9]. High-dimensional entanglement, in particular, provides enhanced information capacity and improved noise resilience [10], making it advantageous for these applications. Although various degrees of freedom—including pulsed modes [11], time bins [12], orbital angular momentum [13], and spatial paths [14]—have been explored in high-dimensional contexts, photonic frequency-bin entanglement offers unique benefits, such as direct generation with integrated microring sources, parallelizability in standard optical fiber, and straightforward measurement with fixed demultiplexers and slow detectors. High-dimensional frequency-bin entangled photons, known as biphoton frequency combs (BFCs), can be produced through spontaneous nonlinear optical processes [15–17], such as comblike spectral filtering of broadband biphotons

from parametric downconversion or pumping parametric oscillators like integrated resonators below threshold.

To fully realize frequency-bin QIP, precise line-by-line manipulation and measurement of the BFC states are essential. A critical piece of this objective is the Fourier-transform pulse shaper, which typically leverages a liquid crystal-based spatial light modulator sandwiched between two dispersive elements (e.g., diffraction gratings or prisms) to synthesize arbitrary spectral filters [18,19]. Today a permanent fixture of classical optical applications—ranging from spectroscopy [20] to RF arbitrary waveform generation [21], coherent control of chemical reactions [22] to lightwave communications [23]—pulse shapers have likewise made their impact felt in the quantum domain. Initial experiments shaping the correlation function of entangled photons with homebuilt free-space devices [24–26] have been followed by commercial fiber-pigtailed pulse shapers supporting spectral control with ~ 10 GHz resolution [27–29], as well as spatial control when configured as multioutput wavelength-selective switches (WSSs) [30,31]. Combined with electro-optic phase modulators via the quantum frequency processor paradigm, such pulse shapers can even enable universal QIP in frequency-bin encoding with BFCs as resource states [17,32]. Additionally, optical pulse shaping has facilitated temporal-mode QIP [11,33], playing a critical role in the synthesis of quantum pulse gates through the spectral shaping of classical pump fields [34,35].

Yet, despite pulse shaping's expanding importance to quantum photonics, existing bulk solutions are reaching their limits in terms of size (~ 1 m²) and spectral resolution ($\gtrsim 10$ GHz), constraining prospects for the continued scaling of BFC processing systems to new regimes of dimensionality and circuit depth. Inspired by prior examples in silicon photonics

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¶Legacy.

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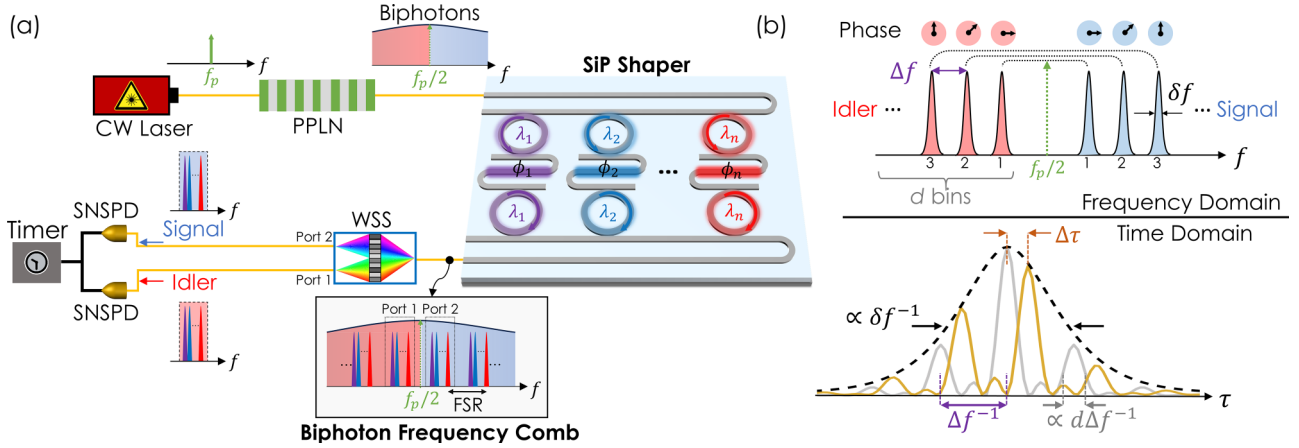


FIG. 1. (a) Diagram of the experimental setup. CW: continuous wave. PPLN: periodically poled lithium niobate. SiP: silicon photonic. FSR: free spectral range. SNSPD: superconducting nanowire single-photon detector. WSS: wavelength-selective switch. (b) Conceptual illustration of high-dimensional frequency-bin states, depicting d coherent superpositions of frequency-bin pairs and their corresponding temporal correlation functions. In this example, linear spectral phases are applied to both signal and idler bins, resulting in a temporal offset (gold) compared to the case with constant phase (gray). See text for details.

[36–38], alternative pulse shaping designs based on microring resonators have been proposed to surmount this impasse. In this concept, microring filters coupled to an input bus waveguide download individual spectral lines, apply phase shifts, and then upload them back to the output waveguide. Nevertheless, pulse shaping of nonclassical light with such a design has proven elusive, due in large part to the technical challenges associated with calibrating and controlling microring filter banks.

This work addresses these challenges by demonstrating on-chip spectral shaping of entangled photons, using a silicon-microring-based pulse shaper previously detailed in Ref. [39]. This device features six independently tunable spectral channels, each incorporating a download microring, an upload microring, and a thermo-optic phase shifter positioned between, for a compact footprint of $\sim(1 \text{ mm}) \times (0.5 \text{ mm})$ per channel. Thermal tuning controls channel frequencies and spectral phase, thus placing the ultimate reconfiguration speed of the pulse shaper in the μs regime (though presently limited by our bias current source to ms-scale reconfiguration times). The frequencies and phases are all precisely precalibrated by multiheterodyne and dual-comb spectroscopy techniques [39].

Carving the spectrum of broadband input biphotons, the pulse shaper realizes line-by-line phase shaping with an ultrafine spectral resolution down to $\sim 3 \text{ GHz}$ —a record for biphoton pulse shaping that facilitates observation of shaped biphoton wavepackets directly in the time domain. By assigning three channels each to the signal and idler photons, we demonstrate fully arbitrary phase control of two frequency-bin qutrits. In all cases, results show excellent agreement with theory, confirming the feasibility of integrated pulse shapers for quantum state control. By incorporating additional microrings with higher quality factors, our basic design can be extended to more channels and finer resolution, as well as combined with other integrated quantum photonic devices for all-in-one processing circuits on chip—circuits that open new opportunities not only in frequency-bin QIP, but also in any context

where precise spectrotemporal mode matching of interacting photons is required.

II. EXPERIMENTAL SETUP

The experimental setup is depicted in Fig. 1(a). We obtain broadband time-energy entangled photons via type-0 spontaneous parametric downconversion in a periodically poled lithium niobate (PPLN) waveguide driven by a continuous-wave laser operating at frequency $f_p \approx 386.8 \text{ THz}$ (775 nm). We couple the biphotons centered at 193.4 THz (1550 nm) onto our silicon photonic (SiP) shaper chip, whose design, programming methods and spectral response are detailed in Ref. [39]. The SiP shaper contains a common input waveguide that directs the broadband biphotons to a microresonator filter bank that downloads spectral slices, applies a phase shift to each with a resistive heater, and then uploads the spectrum to a common output waveguide through a second microresonator filter bank. The resonances of the upload and download microresonators corresponding to the same channel are thermally tuned to align for a bandpass filter, with an alignment accuracy of 250 MHz set by the repetition rate of the classical frequency comb used for calibration [39,40].

The spectral shaper contains six channels with a full-width at half-maximum (FWHM) bandwidth $\delta f = \delta\omega/2\pi \approx 900 \text{ MHz}$ (after both microrings), free spectral range (FSR) $f_{\text{FSR}} = \omega_{\text{FSR}}/2\pi \approx 115 \text{ GHz}$, and an insertion loss of $\sim 6 \text{ dB}$ (excluding fiber-to-chip coupling loss, which we measure to be $\sim 3.5 \text{ dB/facet}$). In our experiment, the pulse shaper both creates the BFC and tunes its phase, but could just as easily shape an independently generated BFC of appropriate spacing. At the output of the SiP shaper, a commercial WSS (WaveShaper 4000S; Finisar) with 10 GHz resolution spectrally isolates and spatially separates the shaped signal and idler bins, which are routed to superconducting nanowire single-photon detectors (SNSPD; Quantum Opus Opus One) connected to a timing module (Time Tagger Ultra; Swabian).

To model the shaped photonic state, we assume each microresonator filter is tuned to a grid spaced by $\Delta\omega$, making the center frequencies $\omega_k^{(s)} = \frac{\omega_p}{2} + (k+B)\Delta\omega$ for the k th signal bin and $\omega_k^{(i)} = \frac{\omega_p}{2} - (k+B)\Delta\omega$ for the k th idler bin, where B is a positive number (not necessarily integer) describing how far the resonances of interest lie from the center of the biphoton spectrum. Under the assumption of nonoverlapping peaks, the complex transfer function is

$$H_\alpha(\omega) = \sum_{k=1}^d \frac{e^{i\phi_k^{(\alpha)}}}{\left[\frac{\gamma}{2} + i(\omega - \omega_k^{(\alpha)})\right]^2}, \quad (1)$$

where $\alpha \in \{s, i\}$ denotes either the signal or idler and $\phi_k^{(\alpha)}$ represents the phase implemented using the inline phase shifter for the bin centered at $\omega_k^{(\alpha)}$. Each term follows a Lorentzian lineshape and is squared to account for both the download and upload rings. Hence, the channel FWHM $\delta\omega$ is slightly smaller than the single-ring FWHM γ , namely, $\delta\omega = 0.644\gamma$. The dimensionality d of the BFC corresponds to the number of physical channels acting on the signal and idler photons, and we have chosen a labeling convention such that energy-correlated bins are assigned the same index k , i.e., $\omega_k^{(s)} + \omega_k^{(i)} = \omega_p \forall k$. An illustration of the BFC spectrum carved by the shaper in this way is shown in the top of Fig. 1(b).

The temporal wavepacket of the BFC can be expressed as [41]

$$\psi(\tau) = \int_0^\infty d\Omega \Phi(\Omega) H_s\left(\frac{\omega_p}{2} + \Omega\right) H_i\left(\frac{\omega_p}{2} - \Omega\right) e^{-i\Omega\tau}, \quad (2)$$

where τ represents the time delay between signal and idler photons, $H_s(\omega)$ and $H_i(\omega)$ are the complex spectral transfer functions defined by Eq. (1), and $\Phi(\Omega)$ describes the spectral amplitude of the initial broadband biphotons. Over the bandwidths of our pulse shaper, we can safely assume $\Phi(\Omega) = 1$ (i.e., constant with uniform phase).

Under these conditions, we obtain (neglecting unobservable unimodular factors)

$$\psi(\tau) = \sum_{k=1}^d e^{i(\phi_k^{(s)} + \phi_k^{(i)} - k\Delta\omega\tau)} \int_{-\infty}^\infty d\Omega \frac{e^{-i\Omega\tau}}{\left(\frac{\gamma^2}{4} + \Omega^2\right)^2}, \quad (3)$$

where we have exploited the nonoverlapping resonance approximation to eliminate all but the energy-matched peaks from the expression. Significantly, the biphoton's frequency correlations cause the phase of the Lorentzian lineshapes to cancel completely, leaving the only nontrivial spectral phases as those applied explicitly by the pulse shaper [$\phi_k^{(s)}$ and $\phi_k^{(i)}$]. Of course, such cancellation does not occur for generic quantum states; the impact of the full phase response has been incorporated in prior analyses [42] of integrated pulse shapers and found consistent with high-fidelity frequency-bin operations.

The correlation function defined as $G^{(2)}(\tau) = |\psi(\tau)|^2$ is proportional to the coincidence rate at delay τ , i.e., the probability of detecting the signal photon delayed by τ with respect to the idler over some infinitesimal window $d\tau$. An example correlation function is portrayed in Fig. 1(b) (bottom) which, following Eq. (3), comprises interferometric terms oscillating

at the interchannel spacing that are multiplied by an envelope whose duration is determined by the inverse linewidth of a single channel. For net zero biphoton phase, $\phi_k^{(s)} + \phi_k^{(i)} = 0$, the wavepacket is peaked at $\tau = 0$ (depicted in gray). The duration of a single fringe is inversely proportional to the total bandwidth of the signal (or idler) half of BFC, or $d\Delta f$. We can then manipulate the biphoton wavepacket through the programmable line-by-line phase control of our SiP shaper. For example, applying the linear phases $\phi_k^{(s)} = (k-1)\Delta\phi^{(s)}$ and $\phi_k^{(i)} = (k-1)\Delta\phi^{(i)}$ causes the fringes under the envelope to shift by an amount $\Delta\tau = (\Delta\phi_k^{(s)} + \Delta\phi_k^{(i)})/\Delta\omega$, as in the gold case in Fig. 1(b).

In our experiment, we perform time-resolved coincidence detection after spatially separating the shaped signal and idler photons, using 20 ps histogram bins, and normalize the experimental correlation functions to account for fluctuations in biphoton flux. The system impulse response, measured and modeled as an 80 ps FWHM Gaussian, is accounted for in all simulation curves, with $\gamma/2\pi = 1.3$ GHz assumed. For further details on the measurement process and impulse response modeling, see Sec. I of Ref. [40].

III. LINEAR PHASES

To apply fully independent spectral phase on the bins for each photon, we program the SiP shaper to transmit two subcombs of $d = 3$ bins at $\Delta f = 3$ GHz spacing with a subcomb center-to-center spacing of $f_{c2c} = 27$ GHz—a multiple of 3 GHz to facilitate phase calibration with our dual-comb heterodyne technique (cf. Sec. III of Ref. [40]). As shown schematically in Fig. 2(a), the signal and idler bins correspond to different subcombs; for the signal photon, the higher-frequency subcomb in its respective FSR is used, while for the idler photon, the lower-frequency subcomb is utilized.

The measured transmission spectrum of the SiP shaper in this configuration is shown in Fig. 2(b), with shading highlighting the 50 GHz-wide WSS passbands used for demultiplexing. We program each phase state according to the calibration procedures in Ref. [39] and record their drive current configurations. For subsequent quantum measurements, we then reload these configurations. Empirically, we have found that the calibration settings remain quite stable over the course of multiple BFC measurement sets ($\gtrsim 40$ min), so no active feedback is implemented [40].

Consider the linear phases $\phi_k^{(s)} = (k-1)\Delta\phi^{(s)}$ and $\phi_k^{(i)} = (k-1)\Delta\phi^{(i)}$ applied across the signal and idler bins, respectively, which shift the fringes under the envelope by $\Delta\tau = (\Delta\phi^{(s)} + \Delta\phi^{(i)})/\Delta\omega$. We first apply linear phase increments to the idler photon $\Delta\phi^{(i)} \in \{0, \pi/2, \pi, 3\pi/2\}$ with zero phase on the signal $\Delta\phi^{(s)} = 0$, as shown in the top row of Fig. 2(c). Next, we apply the same phase increments to both photons, $\Delta\phi^{(s)} = \Delta\phi^{(i)} \in \{0, \pi/4, \pi/2, 3\pi/4\}$, with the measured and simulated temporal correlation functions shown in the bottom row of Fig. 2(c). Note that the phase increments in the second case are halved from the first to produce the same sums $\phi_k^{(s)} + \phi_k^{(i)}$, ideally leading to the same correlation functions despite the distinct physical configurations. As expected, the fringes shift under the envelope by an amount corresponding to the sum $\Delta\phi^{(s)} + \Delta\phi^{(i)}$ rather than individual slopes.

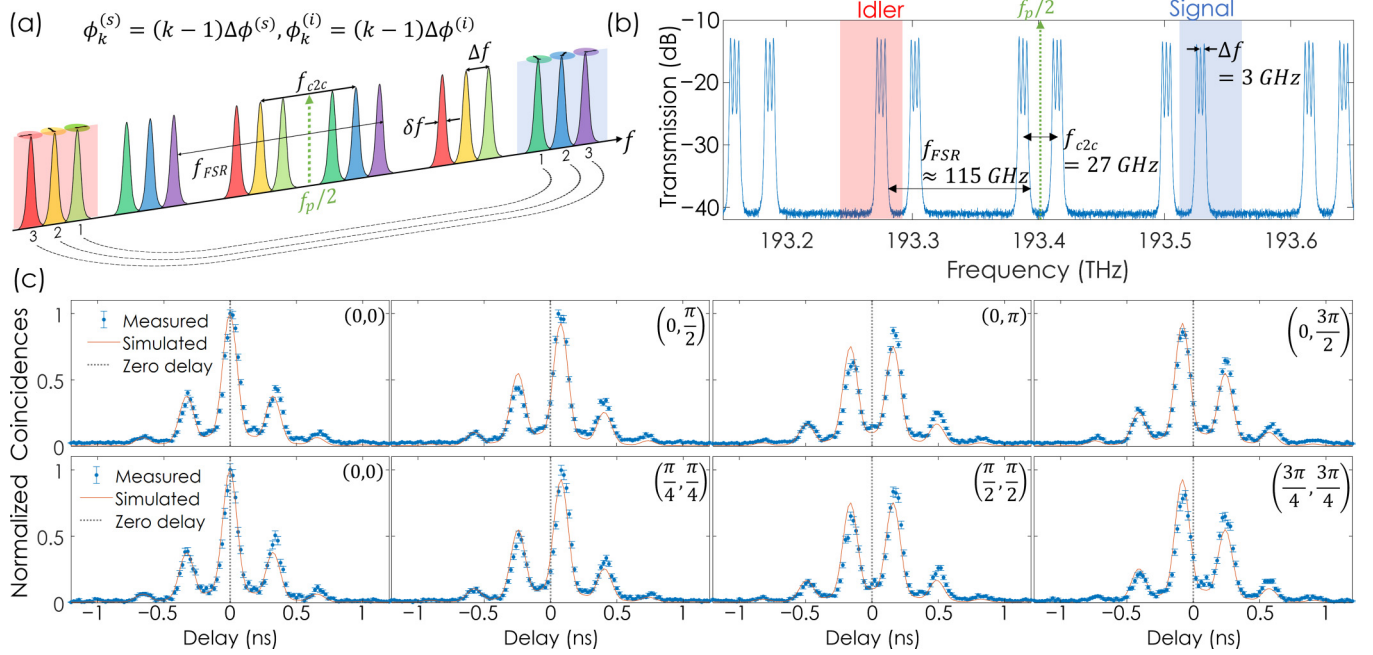


FIG. 2. On-chip pulse shaping results. (a) Conceptual diagram of the pulse shaper channel and phase settings. The channel spacing Δf , subcomb center-to-center spacing f_{c2c} , and spectral phases $\phi_k^{(s,i)}$ are programmable. (b) Normalized transmission spectrum of the SiP shaper programmed to manipulate two subcombs of three bins. Shaded regions indicate the passbands programmed on the WSS. (c) Normalized signal-idler temporal correlation functions for two different phase conditions: (top row) $\Delta\phi^{(s)} = 0$ and $\Delta\phi^{(i)} \neq 0$, and (bottom row) $\Delta\phi^{(s)} = \Delta\phi^{(i)} \neq 0$. The applied linear phase slopes ($\Delta\phi^{(s)}$, $\Delta\phi^{(i)}$) are indicated in the top right corner of each subfigure. The integration time for each histogram is 1 min. The total coincidence rates between ± 1 ns are 340(20) Hz (top row) and 160(30) Hz (bottom row). Error bars assume Poissonian statistics.

IV. NONLINEAR PHASES

Beyond special cases of linear phase which lead to fringe delays, the line-by-line capabilities of the SiP pulse shaper enable more general manipulation of the correlation function as well. To demonstrate this, we proceed with our carved three-bin subcombs but allow only the phase of the central bin of each subcomb [$\phi_2^{(s,i)}$] to vary. The first and second plots in Fig. 3 show the correlation functions when a $\pi/2$ phase is applied across the middle signal and idler bin, respectively, while all the other bins are fixed at zero. The correlation function shows a doubled repetition rate, though the resulting oscillation period (~ 170 ps) approaches the system response (~ 80 ps), thus reducing the contrast.

Next, we apply a $\pi/2$ phase to the middle bin of both signal and idler subcombs, with the results shown in the third plot of Fig. 3. The ideal biphoton phase in this case is identical to the

third column in Fig. 2(c) and indeed results in a similar shape. Finally, we show that the phase applied to one photon can be compensated for by applying an appropriate phase to the other photon by setting the middle signal and idler bin to $-\pi/2$ and $\pi/2$, respectively (last plot of Fig. 3). Measured results align with the same state explored in other configurations shown in Fig. 2(c) (first column).

As an aside, all results presented here leverage the pulse shaper configured such that signal and idler bins correspond to distinct microring filters, thereby allowing our six-channel shaper to attain fully independent control of two qutrits ($d = 3$). However, by considering all filters for both photons, it is possible to shape six bins each ($d = 6$), but at the cost of fully independent control, i.e., bins spaced by a multiple of the FSR experience the same phase. Experiments under this more restrictive condition can be found in Ref. [40].

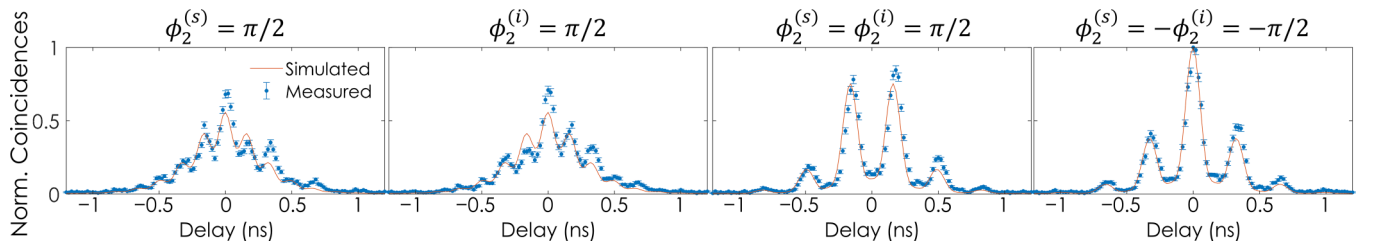


FIG. 3. Normalized temporal correlations measured for distinct signal-idler filters with nonlinear phases. In each case, all phases are set to zero [$\phi_k^{(s,i)} = 0$] except for those listed above the respective plot. The integration time per plot is 2 min, and the coincidence rate over the ± 1 ns window is 132(4) Hz across all four measurements. Error bars assume Poissonian statistics.

V. DISCUSSION

This integrated pulse shaper should find a number of applications in all-photonic QIP. In the context of the quantum frequency processor, such a fine-resolution shaper could enable arbitrary frequency-bin transformations with higher dimensions than possible with bulk components, by increasing the number of frequency bins accessible in smaller total bandwidth and thereby relaxing demands on high-speed electro-optic phase modulation [42,43]. Capabilities like those demonstrated in Fig. 3 could be useful in nonlocal spectral coding or measurement schemes for quantum communications [29,44–46]. In scenarios where photons from an entangled pair are routed to different users, local phase operations by one user can be successfully “decoded” when the conjugate phase is applied by the other user; see, for example, Fig. 3 (last plot) where strong correlations at zero delay are recovered when conjugate phase vectors are applied.

Fundamentally, the complexity of the waveforms any Fourier-transform pulse shaper can produce—i.e., its time-bandwidth product—is determined by the number of independently controllable spectral elements [18,19], which in our case is simply the number of filter channels (six). For a microring-based pulse shaper, the number of independent features is ultimately capped by the number of channels that can be packed within a single FSR ($\omega_{\text{FSR}}/\Delta\omega$), which, at the 115 GHz FSR and 3 GHz spacing in our demonstration, implies that approximately 38 channels could be supported by simply adding more rings and phase shifters. Furthermore, although we have focused on phase-only shaping here, the addition of line-by-line amplitude control should be possible by incorporating variable optical attenuators inline with each phase shifter, components likewise readily available in silicon photonics [47,48].

The performance of the shaper, including both spectral resolution and insertion loss, can be enhanced through careful design adjustments. For a single add-drop microring, the insertion loss at the drop port is set by the overcoupling ratio

Q_i/Q_L , where Q_i is the intrinsic quality factor and Q_L the loaded quality factor. By designing a microring with stronger coupling or by reducing its propagation loss, the ratio increases and the insertion loss is reduced. Additionally, while our current demonstration already achieves a resolution of 3 GHz, notably finer than typical bulk pulse shapers, further refinement is possible by increasing Q_L . With a fixed overcoupling ratio Q_i/Q_L (and thus shaper loss), enhancing the spectral resolution is possible by minimizing the round-trip optical loss within the microrings and tuning the coupling appropriately.

Such higher quality factors can be obtained by further device engineering on the silicon photonics platform, or through other material platforms with ultralow waveguide propagation losses like silicon nitride [49,50] and thin-film lithium niobate [51,52], which could facilitate linewidths (and hence channel spacings) approaching a few tens of MHz and enabling biphoton wavepacket durations of tens of ns. With access to such long time apertures, a pulse shaper of this form could be used to coherently shape photons for interactions with MHz-scale optical cavities or atomic memories [53,54]. To date, photonic wavepacket shaping on these timescales has been the purview of inherently lossy temporal electro-optic intensity modulation [55,56], whereas ultrafine resolution pulse shaping could in principle realize such temporal control with unitary phase-only spectral filters—pointing to exciting opportunities for our system in quantum transduction.

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