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On-Chip Quantum Information Processing with Distinguishable Photons

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Multiphoton interference is at the heart of photonic quantum technologies. Arrays of integrated cavities can support bright sources of single photons with high purity and small footprint, but the inevitable spectral distinguishability between photons generated from nonidentical cavities is an obstacle to scaling. In principle, this problem can be alleviated by measuring photons with high timing resolution, which erases spectral information through the time-energy uncertainty relation. Here, we experimentally demonstrate that detection can be implemented with a temporal resolution sufficient to interfere photons detuned on the scales necessary for cavity-based integrated photon sources. By increasing the effective timing resolution of the system from 200 to 20 ps, we observe a 20% increase in the visibility of quantum interference between independent photons from integrated microring resonator sources that are detuned by 6.8 GHz. We go on to show how time-resolved detection of nonideal photons can be used to improve the fidelity of an entangling operation and to mitigate the reduction of computational complexity in boson sampling experiments. These results pave the way for photonic quantum information processing with many photon sources without the need for active alignment.

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Introduction.—Proposed photonic quantum technologies will require large numbers of photons [1–3] and would benefit from cavity based single-photon sources. Integrated cavities can be used to increase the purity of parametric sources, while reducing their footprint and power consumption [4,5], as well as increasing the generation rates from solid state sources based on two-level systems [6,7]. However, fabrication imperfections produce an inherent misalignment of emission wavelengths from multiple cavity based sources. While thermal [8], strain [9], or electrical [10–12] tuning techniques can be used to adjust the source emission wavelength postfabrication, scaling these techniques to many cavities is impractical; thermal and electrical crosstalk, for example, make aligning even small numbers of resonant sources to the required sub-GHz precision a challenge [5,13–15].

Here, we experimentally address this challenge by demonstrating on-chip quantum interference of photons with distinguishable emission spectra generated from integrated cavity sources. Our approach, which does not use spectral filtering or active tuning, relies on fast photon detection to directly exploit the conjugate relationship between frequency and time: provided photons are detected with a high enough timing resolution, their spectral information can be sufficiently erased to allow quantum interference between initially distinguishable photons [17]. Previous works have applied this technique to narrow-bandwidth cavity emission from atomic systems or parametric processes with frequency detunings limited to tens of MHz [18–20], which is insufficient for the GHz-scale detuning typical of integrated photon sources [12,21]. More recently, experiments with integrated microring resonator (MRR) sources have been realized. Again, these were limited to detunings below the required GHz regime and therefore could only show interference between photons from a single MRR. GHz detunings have been achieved with a single micropillar quantum dot (QD) source; however, these sources are currently not suitable for integration and no scalable application was demonstrated [22]. Here, we demonstrate all the components required for a scalable demonstration of time-resolved frequency erasure: namely, we show that commercial superconducting nanowire single-photon detectors (SNSPDs) enable the erasure of spectral distinguishability at the GHz scale for photons generated in multiple standard integrated MRR sources. We highlight the viability of this approach for photonic quantum information processing by performing a range of on-chip experiments using distinguishable photons from multiple MRR sources, including time-resolved
two-photon interference leading to error-mitigated photonic fusion operations, and boson sampling experiments with up to three interfering (six detected) photons. These results demonstrate that fast detectors can deliver powerful error mitigation for cavity-based sources, and can readily be extended to deterministic photon sources in heterogeneous photonic quantum information processors.

Time-resolved interference theory.—It has been shown for Hong-Ou-Mandel (HOM) interference that provided photons are detected exactly coincidentally at the output ports of a balanced beam splitter, bunching can be observed with photons of arbitrary and, in general, different spectrotemporal profiles [17]. Expressions for time-resolved interference statistics have since been extended to more photons and to include spectral impurity [23,24]. The probability of detecting \( N \) photons with arrival times \( \vec{t} = (t_1, \ldots, t_N) \) at the outputs of a linear optical interferometer described by scattering matrix elements \( T_{ij} \) is [25]

\[
P_{\text{conc}}(\vec{t}) = |\text{Perm}(A)|^2, \tag{1}
\]

where the matrix \( A \) has elements given by \( A_{ij} = T_{ij} \zeta_j(t_i) \) and \( \zeta_j \) is the temporal profile of the \( i \)th input photon. From this we see the complexity of quantum interference, arising from the calculation of permanents of complex matrices, is retained, even if the photons have different spectrotemporal profiles. This effect can be applied in the context of boson sampling [23,27–30] and also for entanglement swapping [20]. The complexity of Eq. (1) will be degraded by the imperfect timing resolution of detectors and time tagging electronics, characterized by the full width at half maximum (FWHM) of their response functions, often called the “jitter”.

Experimental setup.—A schematic of the integrated photonic device is shown in Fig. 1(a). A pulsed pump laser is used to generate pairs of single photons through spontaneous four-wave mixing (SFWM). The laser is filtered and amplified before being passively split on-chip by a tree of multimode interference couplers, designed to implement balanced beam splitters, and pumping up to four silicon MRR sources, with resonance widths of \( \sim 3.8 \) GHz. The spectra of these sources can be individually tuned by voltage-controlled thermo-optic phase shifters, and low-power continuous wave (cw) lasers are used to monitor and align the ring resonators to the desired emission wavelengths. Asymmetric Mach-Zehnder interferometer (AMZI) filters separate signal and idler wavelengths before the signals are coupled off-chip and the idlers enter a programmable integrated interferometer [see Fig. 1(b)]. Photons are detected by high efficiency and low jitter SNSPDs from PhotonSpot, with an average per-detector

![Figure 1](https://example.com/figure1.png)
jitter measured to be $\sim 75$ ps. Timing logic is performed by a Swabian Ultra II time-tagger, with single channel jitter of $\sim 15$ ps. More detail on the experimental setup is given in the Supplemental Material [25].

**Fusion gates with time-resolved complex Hadamard interference.**—We first demonstrate the use of time-resolved techniques to enhance a key building block for photonic quantum computing: the type-II fusion gate [31,32]. Type-II fusion gates perform a partial Bell state projection on two qubits, and can be used to fuse two resource states into a larger entanglement structure [see Figs. 2(c) and 2(d)]. They play a central role in the generation of complex entangled structures for linear optical quantum computing [2], as well as for generating entanglement in solid state systems [36] and in quantum repeater networks [37,38]. The photonic circuitry for type-II fusion gates can be performed by a four-mode complex Hadamard interferometer. This type of circuit, depicted in Fig. 2(a), exhibits interesting multiphoton quantum interference features [39,40], and finds extensive uses in classical encryption [41,42], dense coding [43], and the search for mutually unbiased bases [44]. We investigate how such features appear in a time-resolved complex Hadamard interference and analyze their use for fusion gates. We detune two input MRRs by 55 pm (6.8 GHz) and measure the output arrival times as the internal phase, $\phi$ is varied. This internal phase changes the Bell state that is projected onto and shifts the relative delays $\tau$ at which destructive interference suppresses coincidences [25]. In Fig. 2(e), we plot histograms of the interfering photon’s relative arrival times and see how the complex Hadamard phase shifts the interference fringes as expected. We see good agreement between our model and measured histograms with an average statistical fidelity of $0.972 \pm 0.002$. By integrating over the measured histograms we recover a two-photon interference fringe and by changing the integration window we change the effective timing resolution of the experiment. We see that decreasing the timing window increases the interference visibility, reaching a maximum of 0.6. This maximum visibility is limited predominately by the jitter of our detectors [45]. This measurement probes the interference in a type-II fusion gate acting on a pair of dual-rail encoded photonic qubits initialized in the $j^0i^1$ input state. We can map the visibility of the fringe in Fig. 2(b) to the fidelity of the fusion gate as $F = (1 + \gamma)/2$ with $\gamma = 2V/(1 + V)$ [46]. From the experimental fringe in Fig. 2(b), we observe a significant improvement of the fusion gate fidelity, from $0.79 \pm 0.02$ to $0.875 \pm 0.004$, when tuning the timing window. Temporal filtering in this way allows us to estimate the fusion gate fidelity. In practice, however, this

\[
\frac{1}{\sqrt{2}} (|00\rangle - |11\rangle)
\]
results in a reduction of photon count rate and therefore the gate success probability. If, instead, a large timing window is used but the photon arrival times are measured precisely, then differences in the relative arrival times of the photons represent a random but heralded phase on the remaining photons and so can be accounted for with adaptive measurement [20,47]. In this case, all photons are used and there is no reduction in rates associated with an increase in interference strength.

Boson sampling with spectrally distinguishable photons.—We now investigate the interference of multiple spectrally distinguishable photons in boson sampling tasks. Boson sampling is a model for quantum computation that, although not universal, can challenge the capabilities of classical computers, and is a leading approach to demonstrating quantum advantage [48–51]. In this work we consider the original envisioning along with the scattershot variant [52]: spontaneous sources are connected to the inputs of an interferometer and, when pumped simultaneously, a subset will generate photon pairs.

We use Bayesian updating to validate the experiment. Throughout we use test models that contain quantum interference, involving permanents of complex matrices, and adversarial models based on distinguishable scattering, calculated from permanents of positive real matrices [25]. We note that to counter the sensitivity of the verification to zero probability events that can occur due to experimental imperfections, we include a small noninterfering contribution in our test models [25]. To perform two-photon scattershot boson sampling, we align rings 1 and 4 to the same wavelength, and then rings 2 and 3 are aligned to another wavelength detuned by 54 pm [6.7 GHz, see Fig. 3(g)] and program the interferometer to implement the complex Hadamard transformation. We record the time tags for heralded two-photon events and, as earlier, can apply temporal filtering to coincidence histograms in post-processing. In Figs. 3(a)–3(d), we show the measured output distribution as a function of timing window.

FIG. 3. Scattershot boson sampling with temporal filtering (a)–(d) Measured probability distributions for varying timing windows. (e) Theoretical output distribution for the adversarial model. (f) Corresponding test model distribution. (g) Spectral alignment of the four MRRs relative to the pump pulse (dotted line). (h) Final Bayesian probability for larger sample lists (2000 randomly chosen samples, averaged 300 times). For a timing window of 20 ps the entire sample list was used.
photon number experiments impossible. Now, however, as all samples are valid, we can perform three-photon boson sampling. Here, we pump three MRRs and reduce the detuning to 5.9 GHz to ensure sufficient brightness due to a larger overlap with the pump. We also program a different interferometer to break the symmetry between indistinguishable and distinguishable distributions in $F_4$ [25]. Because of the lower total number of events, we show the cumulative sample-by-sample probability that the data were drawn from the desired distribution. This dynamically updated confidence is shown in Fig. 4(b), showing that our samples were more likely drawn from the interfering distribution.

Discussion.—We have demonstrated photonic quantum information processing experiments with multiple MRRs detuned up to 6.8 GHz and with photon linewidths of $\sim$3.8 GHz. We employed nonscalable temporal filtering approaches to directly compare to the indistinguishable case and assess the inherent timing uncertainty in our setup. Beyond this, we also demonstrated a scalable approach to boson sampling where all samples are valid and point to how the introduction of feed forward would allow the fusion gate to also be operated in a scalable manner, where all detected counts are valid. MRRs are promising candidates to produce high photon numbers [54], but experiments have been limited to small numbers of sources due to the experimental challenge of aligning many sources [13]. To perform experiments with no active alignment of MRRs, we require that the maximum detuning, given by half the resonator free spectral range, is less than the maximum possible frequency erasure [55]. In this work we observe quantum interference with visibilities up to 0.6 limited by the detector jitter, measured to be $\sim$75 ps [45]. This interference is seen with photons detuned by approximately twice the photon linewidth, fulfilling this condition.

Further analysis [25] shows that using the lowest jitter currently available from commercial SNSPDs (15 ps) [57], photons detuned up to 190 GHz can result in HOM visibilities above the quantum limit, while photons detuned up to 5.1 GHz can result in visibilities above $\sim$95%, which is sufficient to demonstrate quantum advantage [58]. Using detectors with the lowest reported jitter in the literature (3 ps) [59], we could expect to observe nonclassical interference from photons detuned by up to 300 GHz, and visibilities above the quantum advantage threshold for photons detuned by 29 GHz. This work shows that time-resolved detection can mitigate the demand to actively align resonant sources and significantly reduce device complexity for large scale quantum photonics experiments.

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