optica

Chip-based array of near-identical, pure, heralded single-photon sources

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Interference between independent single photons is perhaps the most fundamental interaction in quantum optics. It has become increasingly important as a tool for optical quantum information science, as one of the rudimentary quantum operations, together with photon detection, for generating entanglement between non-interacting particles. Despite this, demonstrations of large-scale photonic networks involving more than two independent sources of quantum light have been limited due to the difficulty in constructing large arrays of high-quality, single-photon sources. Here, we solve the key challenge, reporting on a novel array of five near-identical, low-loss, high-purity, heralded single-photon sources using spontaneous four-wave mixing on a silica chip. We verify source quality through a series of heralded Hong–Ou–Mandel (HOM) experiments, and further report the experimental three-photon extension of the HOM interference effect, which maps out for the first time, to our knowledge, the interference landscape between three independent single-photon sources.

1. INTRODUCTION

Quantum states of many particles offer an opportunity to study the rich physics of large-scale quantum correlations. Light provides the possibility of building such quantum states under ambient conditions, both because photons are robust to dephasing due to minimal interaction with their environment and one another, and because entanglement can be generated between photons, allowing the observation of strong quantum phenomena in everyday settings [1,2]. Consequently, quantum optical networks are expected to enable new technologies—spanning communications, distributed sensing, simulation, and computation—characterized by performance that dramatically exceeds that of their classical counterparts [3].

Entanglement can be established across such a quantum network through quantum interference of independent single photons and measurement using a photodetector [4]. The archetype of this interaction is the Hong–Ou–Mandel (HOM) effect [5], whereby two photons from independent sources coalesce at a beam splitter, always leaving at the same output. Remarkably, this approach enables the generation of entanglement directly from the bosonic properties of the underlying fields without the necessity for the photons to interact directly.

A key challenge is scaling this approach to generate the large entangled networks necessary in many technological applications. Over the past decade, rapid progress has been made in developing several of the elements necessary to construct such large-scale quantum optical states. High-efficiency photon-counting detectors [6], actively programmable circuits [7,8], and quantum memories have all been demonstrated [9]. A significant remaining obstacle is the demonstration of arrays of many quantum light sources that deliver single photons with low loss, high purity, and sufficient control of the full photonic modal structure to enable high-quality interference.

The main approaches to preparing single photons in such states are either to place a single emitter in a high-finesse cavity or to use a nonlinear optical process by which photons are produced in pairs by spontaneous scattering, and the detection of one heralds the presence of the other [10]. Both approaches offer routes to deterministic photon generation, though the latter requires effective routing of multiple pair sources [11]. Despite this complication, heralded photon-pair sources have become the de-facto standard for generating quantum states of light for networking by virtue of their ease of use and operation in ordinary laboratory conditions.

State-of-the-art experiments have investigated the quantum interference of light originating from three and four independent sources. Experiments of this scale, however, have required source imperfections to be compensated by narrow spectral filtering, long data collection times, and post-selected fidelity measures to show evidence of non-classical behavior [12–14]. These current photon-source limitations have prohibited detailed studies generalizing the HOM effect beyond two independent photons despite its wide-ranging utility in a number of important technologies [8,15–19].

Recently, integration of photon pair sources on-chip has been recognized as one of the most promising approaches to scaling due to the small sizes that can be achieved, direct compatibility with integrated photonic architectures, reduction in required pump power, and potentially exquisite control of the populated optical modes [20–23]. Unfortunately, fabrication imperfections or material limitations frequently spoil this dream. Optical loss is a key parameter for any quantum light source, and on-chip sources frequently suffer from large losses due to high scattering and outcoupling mode mismatch [23–25]. In addition, the phase-matching conditions for the spontaneous scattering process are highly sensitive to optical dispersion. Even small non-uniformity in fabricating the waveguide structure can impart large changes in the joint spectrum of a generated photon pair. Further, poor dispersion control can introduce undesired residual frequency correlations between photon pairs, which reduces heralded state purity and thus the quality of interference. While recent experiments have managed to integrate two [23] and four [22] individual photon pair sources on the same chip, they did not demonstrate the single-photon purity necessary for performing heralded multi-photon quantum interference experiments.

Here, we solve the problem of generating multiple independent *pure-state* photons by means of a microfabricated waveguide array that contains five near-identical heralded single-photon sources. We use these low-loss light sources to map out, for the first time to our knowledge, the entire third-order correlation function arising from the interference of three independent single photons, showing genuine three-particle quantum interference.

2. SPONTANEOUS FOUR-WAVE MIXING IN SILICA

Our source array consists of a series of straight waveguides fabricated by UV laser writing of a silica-on-silicon photonic chip as shown in Fig. 1. The silica waveguides show low propagation loss and guide circular spatial modes that are nearly identical to those of a silica fiber (see inset to Fig. 1). Each source is operated by injecting a pulse of horizontally polarized pump light. Spontaneous four-wave mixing (SFWM) is achieved through birefringent phase matching (see Supplement 1), and generates the desired pairs of photons with vertical polarization. Appropriately matching the pump characteristics and phase-matching condition in the waveguides results in pairs of photons correlated only in their photon number, eliminating any excess frequency–time entanglement [20,26] and thereby enabling heralded photons of high purity without the need for narrowband spectral or temporal filters. We use a Ti–Sapphire laser (SpectraPhysics MaiTai) that outputs nearly transform-limited pump pulse with a 4.5 nm bandwidth, 736 nm central wavelength, and approximately 1 nJ pulse energy operating at an 80 MHz repetition rate to generate photons centered at 670 and 817 nm [see joint spectrum in Fig. 2(b)]. After the chip, the pump is removed with polarizing optics and broadband spectral filters, while the photon pair is divided with a dichroic beam splitter and coupled into separate single-mode optical fibers and detection by avalanche photodiodes (PerkinElmer SPCM-AQ4C). A custom-programmed FPGA (Xilinx SP605 board) is used for coincidence counting among all modes.

Each source is individually characterized by monitoring the two output fibers with silicon avalanche photodiodes (APDs). The heralding efficiency η_H is the probability that if a herald photon is detected, a photon in the heralded mode will also be detected. We measure $\eta_H = 31.6 \pm 0.3\%$ (see Supplement 1), for which the APDs are the dominant source of loss with an estimated detection efficiency of 60% at the idler wavelength. Factoring out the detector loss gives us a preparation efficiency of $\eta_p = \eta_H/0.6 = 52.7\%$, which accounts for all losses from photon generation in our source chip up to and including coupling into a single-mode fiber. We measure a coupling efficiency >80% from the waveguide into these single-mode fibers, which makes this source potentially useful for a range of loss-critical quantum applications [27–29]. Although we observe some fluorescence noise in both modes of the source (see Supplement 1), this can be almost entirely removed by time-gating our measurements to within ~1 ns of the pump. This effectively filters the time-uncorrelated fluorescence signal while not affecting the single photons that have a duration ~1000× shorter than this
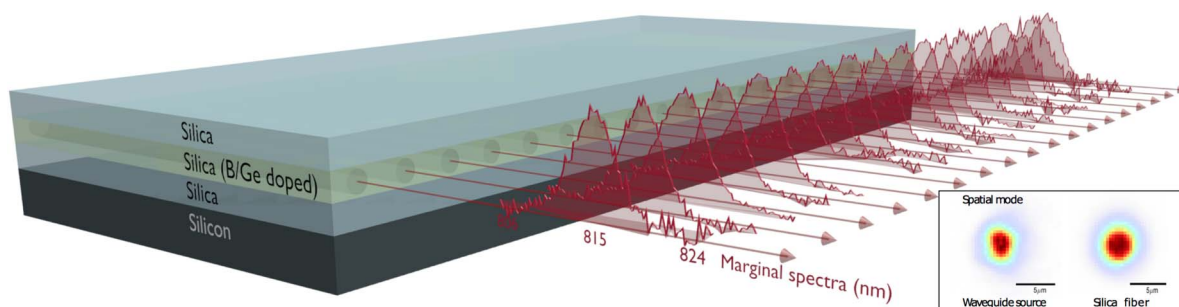

Fig. 1. Array of heralded single-photon sources on a silica photonic chip. A series of straight waveguides are fabricated via UV-laser writing in a germanium-doped silica-on-silicon photonic chip, each of which constitutes its own heralded single-photon source. Spontaneous four-wave mixing (SFWM) is achieved through birefringent phase matching and generates correlated pairs of photons. Each source is pumped using the same pulsed laser centered at 736 nm, and the marginal spectrum of each heralded photon is recorded using a single-photon spectrometer. While 18 sources were fabricated with nearly identical spectra, all quantum interference experiments were performed on a subset of five sources. This was necessary due to constraints imposed by the free-space pump-coupling optics, and was not inherent to the sources themselves. An example output spatial mode of the source and a fiber are shown in the inset with mode diameters of 4.5 ± 0.5 μm and 5.0 ± 0.5 μm, respectively.
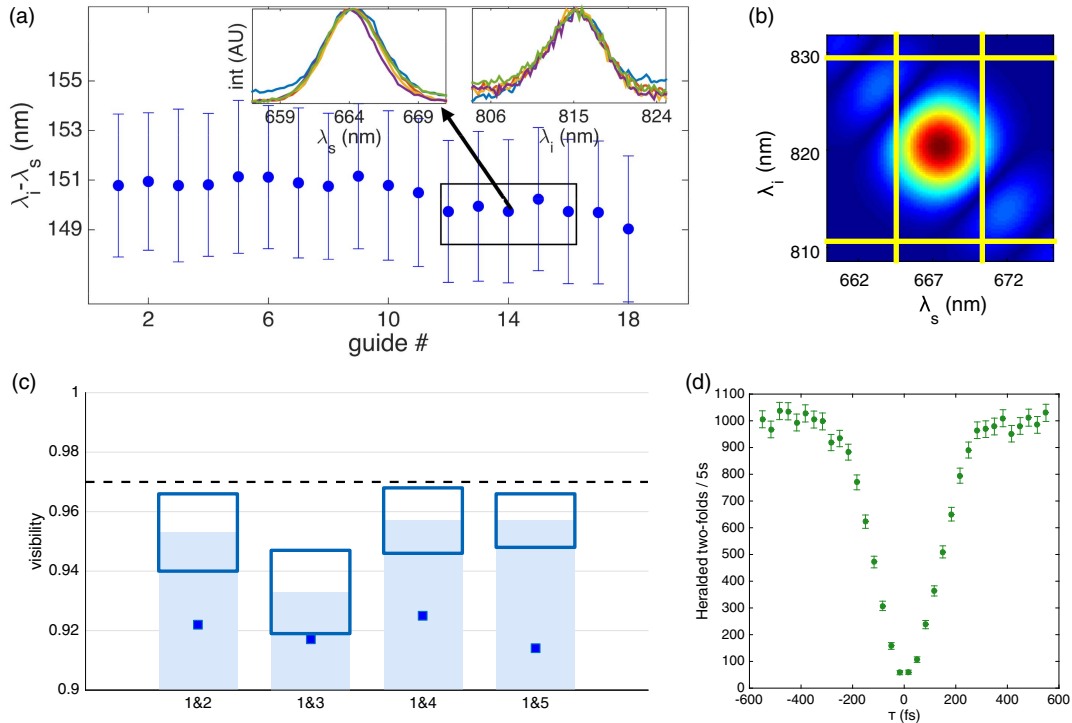
Fig. 2. Heralded HOM interference experiments. (a) The uniformity of UV-written SFWM sources is first quantified by measuring $\lambda_i - \lambda_s$ for 18 different guides on the same chip. The full marginal spectra for each of the 18 idler photons are shown in Fig. 1. The error bars represent the 1σ widths of each marginal spectrum. The five sources shown in the box are selected for the two-source HOM-interference experiments. (b) Calculated joint spectral amplitude (JSA) for our source. The yellow lines indicate the bandpass filters applied to each photon. This filtering removes residual spectral correlations between signal and idler and thus improves the heralded state purity from 87% to 97%. Importantly, >92% of the generated single photons are still transmitted through the filters, which is the basis for our claim that the spectral filters are not narrowband. (c) Results of a series of HOM interference experiments using five waveguides, taking the heralded emission from two sources at a time. Blue bars indicate background subtracted results, while squares show raw visibility results. The maximum expected visibility, $V_{\max}^n = 0.97$, is shown as a dashed line. This upper bound to the visibility is primarily due to the slight angular offset between the two herald photons providing a different bandpass from the shared spectral filters. This is a constraint of our bulk optics and is not intrinsic to the source; using dedicated filters for each individual source would restore $V_{\max}^n > 0.99$. (d) Example of two-source HOM interference data showing the reduction in heralded two-fold coincidences as the optical delay is adjusted.

gating window. In this sense, the temporal filtering used in our experiment is not narrowband. For the remaining work, the shorter-wavelength signal photon is used as the herald photon. We then measure a heralded intensity autocorrelation $g_H^{(2)}(0) = 0.03 \pm 0.01$ of the heralded field. This result clearly violates the classical bound of $g_H^{(2)}(0) \geq 1$ and is close to the ideal value for a single photon of $g_H^{(2)}(0) = 0$, signifying good source performance, with the predominant error arising from multipair generation. At these conditions, heralded photons are detected at a rate of $\sim$200 kHz.

While these excellent single-source characteristics are a prerequisite for use in any quantum-enhanced protocol, it is the construction of a large array of well-matched sources that has so far hindered the scaling of quantum photonic experiments. Critically, in the present device, we find that the phase-matched wavelengths of the signal and idler photons for each of our sources are highly uniform, indicating a nearly constant birefringence across the entire silica-on-silicon wafer. The fabrication of the wafer by flame hydrolysis deposition is a well-developed technique widely used in classical photonics [30]. This method achieves a uniformity of the substrate birefringence of $\delta(\Delta n) < 1 \times 10^{-6}$, which allows us to construct and operate an unprecedented number of identical single-photon sources on the same chip.

As an exacting test that these waveguides are truly indistinguishable sources of pure single photons, a series of heralded two-source HOM interference experiments are performed pairwise between five different sources on the same chip, as shown in Fig. 2. The output of each of four sources is interfered separately with a common reference source on a balanced fiber beam splitter to confirm near-identical, high-purity emission among the entire set. An FPGA loaded with a home-built coincidence counting program monitors the four-fold detection events as an optical delay stage is scanned to record the HOM interference curves (see Supplement 1). From the HOM curve, we calculate the interference visibility as $V = (P^{(\infty)} - P^{(0)})/P^{(\infty)}$, where $P^{(\tau)}$ is the measured coincident probability at a time delay τ. The experimentally observed interference visibilities closely match theoretical predictions in all cases, while the similarity of raw and background-subtracted visibilities is consistent with minimal noise in heralded emission.

3. INTERFERENCE OF THREE HERALDED SINGLE PHOTONS

This breakthrough in single-photon source engineering—an array of near-identical, pure, heralded single-photon sources with sufficiently low loss and high brightness to operate many of them

simultaneously—allows us to go beyond previous studies of two-photon interference and explore the critically important regime of interference of multiple, independent single photons. This class of interference underpins all linear optical quantum communications, simulation, and computing schemes, and obtaining high-fidelity operations based on interference is vital to understanding the possibilities for scaling photonic systems to a usable capacity. Here, we show that our platform provides a route to large-scale photonics by performing an in-depth study of the entire interference landscape of three heralded photons for the first time, to our knowledge. The quantum interference of three heralded single photons is studied by injecting the photons into a balanced three-port beam splitter (a fiber-based tritter). The action of this tritter is described by a unitary matrix that maps the input field operators $\hat{a}_i^\dagger$ to the output field operators $\hat{b}_i^\dagger$ with $\hat{b}_i^\dagger = \Sigma_j \mathcal{U}_{i,j} \hat{a}_j^\dagger$, where the fiber tritter implements the unitary transformation

$$\mathcal{U} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & e^{i2\pi/3} & e^{i4\pi/3} \\ 1 & e^{i4\pi/3} & e^{i2\pi/3} \end{pmatrix}. \qquad (1)$$

By varying the optical time-delay of the input states, we measure the full time dependence of the third-order correlation function for each possible output combination. Six-fold coincidence counts are recorded as a function of the two time delays using an array of silicon APDs and our FPGA counting unit. A second fiber-tritter is connected to one of the output modes to achieve pseudo photon-number resolution. The signal modes of each source pass through a broad spectral filter ($\Delta\lambda \sim 10$ nm), the bandwidth of which is larger than the full width of the marginal spectra. This increases the purity of the heralded photons without significantly reducing the source brightness [20]. The results of this three-photon generalization of the HOM experiment are shown in Fig. 3.

Due to the low losses in our experiment, we detect simultaneous emission of single photons by multiple sources at a high rate. The average six-photon coincidence count rate corresponding to the data presented in Fig. 3 is 0.41 Hz, which allows us to collect enough data to resolve the entire landscape of the third-order correlation function for the first time, elucidating some subtle new features. This six-fold count rate includes losses from the two fiber tritters needed to perform the interference experiment and is also reduced due to our reliance on pseudo-number resolving detectors (see Supplement 1). Using the same pump power, the six-fold coincidence count rate into six single-mode fibers using APD detectors is approximately 2 Hz. Attempting to run all five sources simultaneously, assuming the same pump power and losses, would produce a ten-photon coincidence rate of 17 μHz. While this is too low to acquire reliable data, experimental upgrades that are possible in the near future could make such experiments feasible. For example, using superconducting nanowire detectors with a detection efficiency of 90% and providing antireflection coatings on the chip and fiber surfaces would allow our source to achieve a ten-photon detection rate of approximately 0.01 Hz, which corresponds to 864 ten-photon events a day. While arrays of identical sources are a valuable asset for active multiplexing with switches or memories [11,31], these numbers show that optimized experiments can potentially increase to yet-higher numbers of heralded single photons without the complexity of multiplexing.
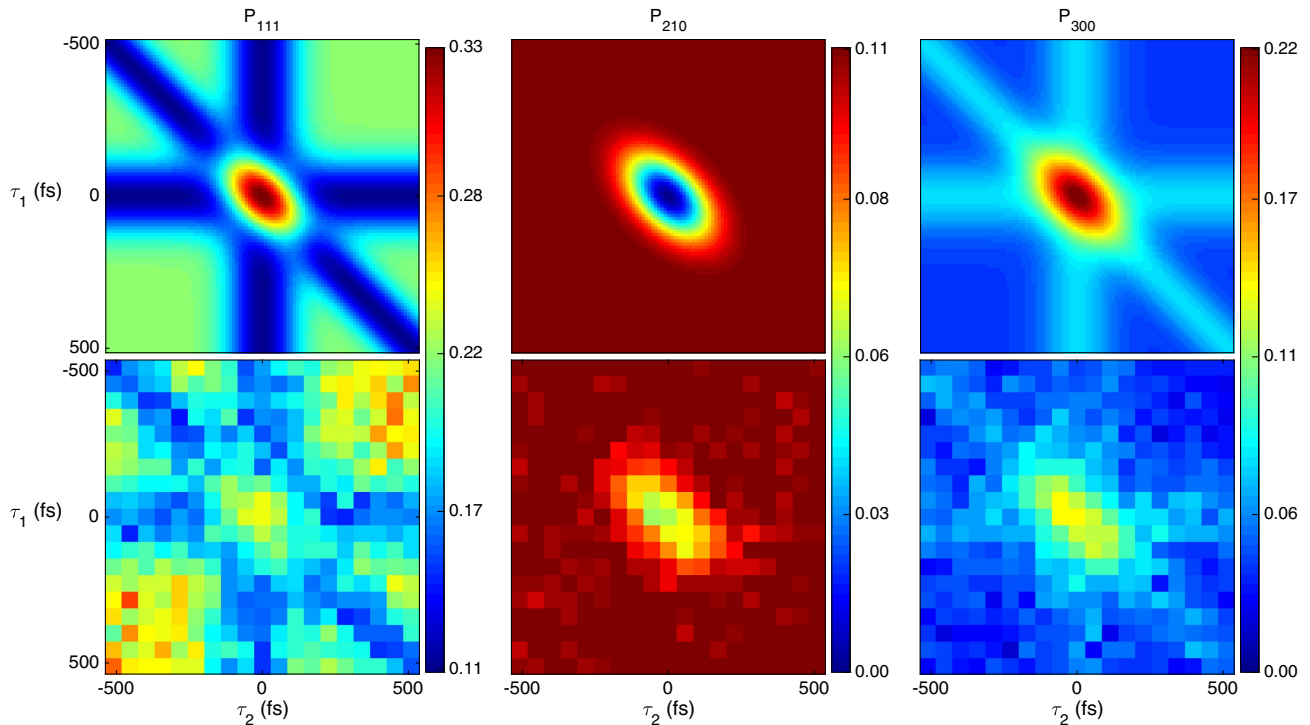

Fig. 3. Experimental interference of three independent heralded photons in a tritter. Top: Theoretical output probabilities P_{111}, P_{210}, and P_{300} for ideal single Fock state inputs as a function of the delays of the impinging photons. Bottom: Measured three-photon interference data. The data constitute over 340,000 six-photon events detected in 10 days, a data rate of 0.41 Hz, using commercial APDs. Three heralded photons are coupled to a 3 × 3 fiber splitter, with the resulting number statistics collected as two delay stages scanned through the point of maximum indistinguishability (plot centers). Pseudo-number resolution is obtained (for N_{210} and N_{300}) by relying on additional fiber beam splitters and extra APDs.

While three-photon interference has been observed in previous experiments [15,19], the results presented here advance the state-of-the-art in two key ways. First, our high-quality, on-chip source array allows these experiments to be performed in a fully heralded, and thus scalable, fashion by operating three sources simultaneously. Second, despite the low probability of simultaneous emission from three spontaneous sources in this heralded configuration, the low loss of our sources still allowed a full mapping of the three-photon interference landscape shown in Fig. 3. To our knowledge, this result has never been previously demonstrated; previous works using two sources in a non-heralded configuration probed this third-order correlation at a few individual points. Leveraging this advance in source engineering to immediately obtain novel quantum interference results highlights the benefits of on-chip source integration.

The complicated structure of even these third-order correlation functions is indicative of the complexity of collective many-photon interference [32]. The $|111\rangle$ and $|300\rangle$ output results in Fig. 3 allow us to directly observe the non-monotonic behavior of the correlation functions, as the distinguishability of the photons is changed by adjusting the relative delays of the interfering photons. Such behavior is realized only for quantum interference between more than two photons [33]. Further, this full correlation function clearly shows the distinction between two- and three-photon interference. In particular, we find the $|210\rangle$ output term is time-delay invariant if one photon always remains distinguishable. The complete absence of any two-photon interference effect is accompanied by a three-photon interference term which theoretically has unit visibility. We find that this dip occurs when all photons arrive simultaneously (i.e., $\tau_1 = \tau_2 = 0$), and provides strong evidence for genuine three-photon interference. In fact, the suppression of this $|210\rangle$ term derives from the more general Fourier suppression law [34] that has been suggested as a stringent test of the genuine quantum interference between many single photons [35]. Importantly, it has been shown that these two- and three-photon correlation functions are sufficient to fully characterize an arbitrary number of sources [36].

4. DISCUSSION

A full model was constructed to analyze the dependence of photon statistics on residual photon distinguishability, purity, and higher-order SFWM pair emission (see Supplement 1). The results from this model are shown in Fig. 4. In order to quantify our experimentally observed three-photon visibilities, we ran a separate experiment setting $\tau_1 = 0$ and adjusted τ_2 to introduce complete distinguishability. This one-dimensional scan allows collection of sufficient data to determine the three-photon interference contrast with high precision. The results are plotted in Fig. 4. The expected visibilities for classical, phase-averaged, coherent state inputs are calculated and plotted as white circles. The magnitudes of the measured visibilities clearly exceed these classical bounds. The experimentally measured effective squeezing parameter and source loss was used to model the effects of higher-order SFWM pair emission (see Supplement 1). Further, the expected photon state purity as calculated from the theoretical joint spectral amplitude, together with the overlap of the measured marginal spectra, were used to include the effects of residual distinguishability and mixedness (see Supplement 1). The results from this model are plotted as gray shaded boxes and agree very well with our measured results, confirming we have understood
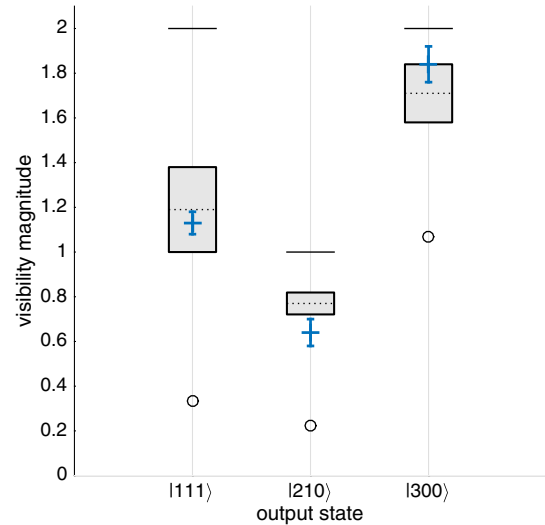

Fig. 4. Measured and modeled interference visibilities. For all results, $\tau_1 = 0$ and τ_2 is scanned and the magnitude of the visibility is plotted. Our measured results are shown by the blue crosses. The black dashed line represents the modeled visibility for three single photons, including the effects of higher-order pair emission and residual distinguishability. The errors on this model were estimated using a Monte-Carlo method, taking into account the uncertainties in the model parameters. Black solid lines indicate the maximum theoretical visibility for ideal Fock state inputs for which the full interference landscape is plotted in Fig. 3. White circles indicate the maximum visibilities for classical coherent state inputs.

the primary sources of error. Importantly, we find that over 90% of the visibility reduction is due to higher-order pair emission, which can be made arbitrarily small by reducing the pump power per source or using photon-number-resolving detectors on the herald arm.

5. CONCLUSION

In conclusion, we have demonstrated a new platform for constructing large numbers of identical heralded single-photon sources. The ability to operate these arrays of low-loss, high-purity, on-chip sources will be increasingly critical as experiments scale to building and manipulating yet larger quantum states of light. This advancement in source engineering has already allowed us to map out, for the first time to our knowledge, the three-photon generalization of the HOM interference landscape between independent photons. Our modeling indicates that the observed visibilities are a result of true tripartite interference and highlight the importance of minimizing loss not only for increasing data rates, but in reducing the relative contribution of multi-pair emission to the observed click statistics. This source architecture also supports heralding of photons at telecom wavelengths [20]. For example, pumping SFWM sources with a laser operating at one micrometer central wavelength would allow, for an appropriate birefringence, production of a visible signal photon as herald and a telecom-heralded photon suitable for long-distance propagation. Such lasers are available with a higher repetition rate than used here, which also allows a higher heralding rate while keeping $g_H^{(2)}(0)$ low [37,38].

Our results benefit both future source-engineering and fundamental science efforts. Such source arrays are an important

component in engineering near-deterministic photon sources through active multiplexing [11,31]. These would be useful in a wide range of quantum-enhanced technologies including metrology [28], communication [39], simulation [40], and computation. However, even without multiplexing, an array of sources like that presented here is a valuable tool for probing the computational power of quantum systems [41–43].

Data contained in the figures are available from Dataset 1, Ref. [44].

See Supplement 1 for supporting content.

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44. Data contained in the figures are available from https://doi.org/10.5287/bodleian:2NQayR8De.