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Generation and sampling of quantum states of light in a silicon chip

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Implementing large instances of quantum algorithms requires the processing of many quantum information carriers in a hardware platform that supports the integration of different components. While established semiconductor fabrication processes can integrate many photonic components, the generation and algorithmic processing of many photons has been a bottleneck in integrated photonics. Here we report the on-chip generation and processing of quantum states of light with up to eight photons in quantum sampling algorithms. Switching between different optical pumping regimes, we implement the Scattershot, Gaussian and standard boson sampling protocols in the same silicon chip, which integrates linear and nonlinear photonic circuitry. We use these results to benchmark a quantum algorithm for calculating molecular vibronic spectra. Our techniques can be readily scaled for the on-chip implementation of specialised quantum algorithms with tens of photons, pointing the way to efficiency advantages over conventional computers.

Devices that address customised problems with quantum algorithms are expected to demonstrate an efficiency advantage over conventional computers. Boson sampling is a specific model of quantum computing that is suited to the platform of photonics [1–5] and has been mapped to the calculation of molecular vibronic spectra [6], simulation of spin Hamiltonians [7], simulation of molecular quantum dynamics [8], and the enhancement of classical optimisation heuristics [9]. Implementing such applications at a size that challenges conventional computers [10] demands the integration and high fidelity operation of a large number of different components, including circuitry [11–13], detectors [14], filters [15], and photon sources [16, 17]. The low efficiency of individual spontaneous photon sources has motivated the adoption of deterministic solid-state photon sources [18–21]. However, the low-loss integration of solid-state sources into photonic circuitry is an on-going challenge.

Creative approaches to realise boson sampling with high numbers of photons from spontaneous sources have seen the design of variant models. In principle, the simultaneous optical pumping of a number k of spontaneous sources that exceeds the number n of desired photons, boosts the overall rate of photon-pair production combinatorially. In Scattershot boson sampling (SBS) [22–24], one photon from each pair heralds the location of its partner, such that a Fock state of n photons is prepared over a random subset of modes. In Gaussian boson sampling (GBS) [25], k single mode optical nonlinearities are coherently pumped to produce k modes of squeezed (vacuum) light, before linear optical processing and n -photon detection at the output.

The complex photonic circuitry required to scale these approaches can be addressed with integrated photonics. Here, by pumping 4 integrated spontaneous four wave mixing (SFWM) sources with either a single-colour or a two-colour laser, we select between the Fock state required for SBS and the squeezed state required for GBS. Both states of light are routed on-chip to the same linear optical circuit, which implements a random unitary operation over 12 waveguides. In the GBS mode of operation, we benchmark this class of device for calculation of vibronic spectra. In the limit of the SBS mode of operation, with $n = k = 4$, we implement standard boson sampling with 4 heralded photons, generating and processing 8 photons on-chip. Our analysis shows that larger versions of our silicon photonic chip, that exploit the combinatorial boost in photon rate available through the SBS and GBS protocols, open up the regime of efficiency advantages over conventional computers.

The silicon circuitry and configuration of these experiments can be understood with reference to Fig. 1. Four SFWM spiral sources are coherently pumped by on-chip splitting of the near-1550 nm pump laser via multi-mode interference (MMI) near 50:50 beam-splitters; pump light is then removed by asymmetric Mach-Zehnder interferometers (AMZIs). In the dual-wavelength pumping (GBS) scheme (where photons are generated at the same signal wavelength) two spectral regions of the temporally compressed (spectrally broadened) pump are selected and recombined using wavelength-division multiplexers (WDMs), before injection to the chip. In the single-wavelength pumping (SBS) scheme, (where signal and idler photons are generated at different wavelengths)

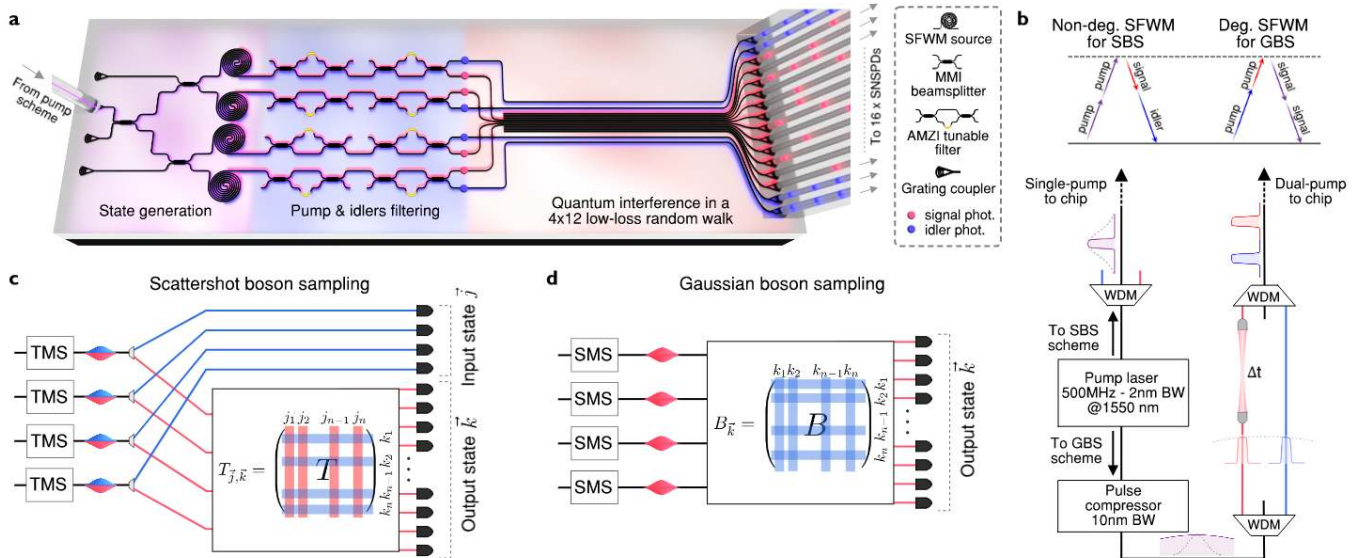


FIG. 1. Silicon photonic chip and experimental configuration. (a) The silicon chip integrates four SFWM spiral photon sources and twelve continuously coupled waveguides with a network of MMIs and grating couplers; AMZIs separate idler (blue) and signal (red) photons, and remove pump light (purple). (b) The SBS pumping scheme, where two-mode vacuum squeezing (TMS) is generated via non-degenerate SFWM, comprises a 1550 nm laser with a bandwidth of 2 nm, and a WDM for wavelength selection. In the GBS scheme, which relies on single-mode squeezing (SMS) generation via degenerate SFWM, a pulse compressor increases the bandwidth to 10 nm, WDMs select dual wavelengths, and a delay line synchronises the arrival of the two pulses. (c) In a given run of the SBS protocol, the detection pattern \vec{j} measured in the idler modes heralds the modes in which signal photons enter the random walk. The probability to measure a given pattern \vec{k} after the random walk (described by a unitary matrix T) is related to the permanent of a sub-matrix of T , whose rows and columns are defined by \vec{j} and \vec{k} respectively. (d) In a given run of the GBS protocol, four single-mode squeezed states are generated and delivered to the random walk. The probability for a given measurement pattern in the GBS protocol is given by the Hafnian of sub-matrices of B , which is a function of both T and the squeezing parameters.

idler photons are separated using a second layer of AMZIs and out-coupled to a fibre array to herald the presence of the signal photons. In both regimes, signal photons are routed to the four central modes of a continuous random walk, implemented over 12 evanescently coupled waveguides, then out-coupled to the fibre array. Ultra low-loss out-coupling is implemented by aluminium assisted apodized grating couplers [26, 27]. An array of 16 superconducting nano-wire single-photon detectors (SNSPDs) with approximately 78% efficiency detect the 4 heralding modes and the 12 modes from the random walk. (See Supplementary Materials for details).

The SBS protocol is designed to tackle the inefficiency that results from implementing standard boson sampling with spontaneous photon sources [22]. In the original model of boson sampling [1], a linear optical circuit is configured to implement a random unitary operation over m modes. A number $n < m$ of input ports are each populated with a single photon, such that n photons undergo an $n \times m$ random operation, before detection with photon counters. Because the probability amplitude for each n -photon transition is equal to the permanent of the corresponding transfer matrix, which is in general intractable to classical computation, an ideal experiment would efficiently produce samples from an essentially classically

forbidden probability distribution. However, the rate at which the required n -photon state is produced with spontaneous sources decreases exponentially with n . As shown in Fig. 1c, the SBS protocol addresses this inefficiency by pumping k sources that each produce weak two-mode squeezed light (with $n < k \leq m$). One (idler) photon from each pair is directly detected to identify the input port of its partner (signal) photon. In comparison to the original scheme, the probability to generate n -photons is boosted by a factor $\propto \binom{k}{n}$ [22, 23].

We implemented the SBS protocol in our silicon chip, with $k = 4$ sources, using the single wavelength pumping scheme shown in Fig. 1b. The experimentally measured distribution for the $n = 3$ case (6-photon events) shown in Fig. 2a, has a mean fidelity [11] with the theoretical distribution of 92%. Figure 2b shows the measured difference in photon pair generation rates between the SBS and standard boson sampling (where only n sources are pumped) protocols for $n = 1$ to 3, and for $n = 4$ where the two regimes converge. As predicted, the n -photon pair generation rate, is enhanced by a factor of approximately $\binom{4}{n}$. In the SBS regime, the two-pair and three-pair photon rates were measured at 5.8 kHz and 4 Hz, respectively, while the 4-pair (8-photon) rate was approximately 4 events per hour. The average purity

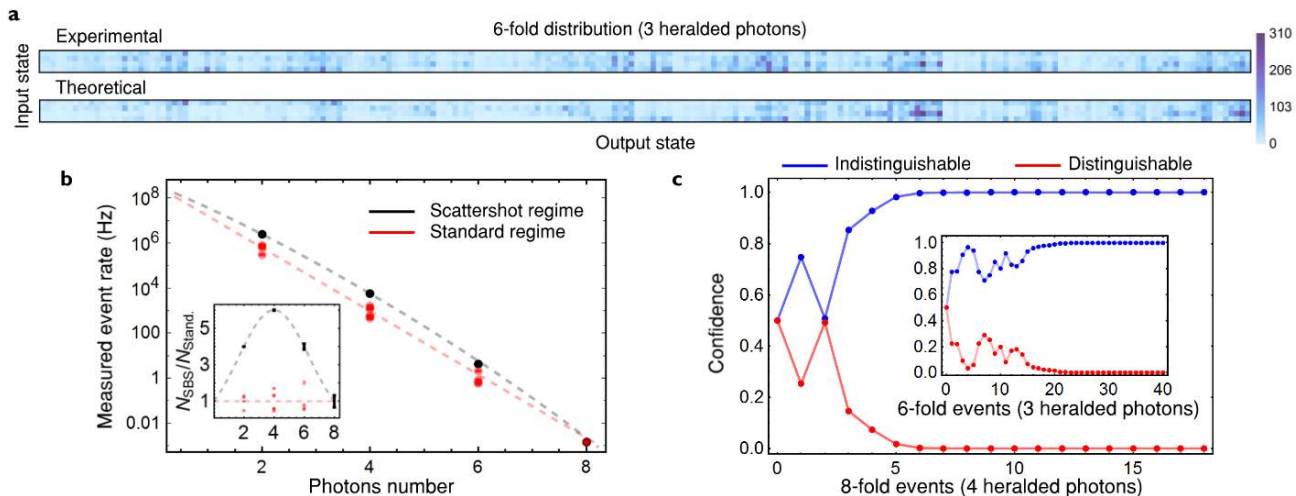


FIG. 2. Results for Scattershot boson sampling. (a) Experimental and theoretical distribution for six-photon events, with anti-bunched states (one photon per detector) on horizontal axis in increasing order $\{(1, 2, 3), (1, 2, 4), \dots, (10, 11, 12)\}$ from left to right; input states on the vertical axis are $\{(1, 2, 3), (1, 2, 4), (1, 3, 4), (2, 3, 4)\}$ from bottom to top. (b) Measured event rates for 2 to 8 photons are shown for the SBS (black points) and standard (red points) regimes, with a dashed line fit. Inset is the photon rate enhancement for SBS over the standard boson sampling protocol. (c) Dynamic Bayesian model updating for validation that statistics are from indistinguishable rather than distinguishable photons for 8-photons (and 6-photons inset).

of the signal photons, estimated via unheralded second-order correlation measurements [28], was calculated at 86%. (See Supplementary Materials for details).

While fidelity comparisons with theoretical distributions are not a scalable method of validating boson sampling, an efficient alternative is to compare measurements against those predicted by a classically tractable and plausible distribution. As shown in Fig. 2c, we used Bayesian model comparison [11, 23, 29–31] to validate our $n = 4$ (8-photon) statistics against those predicted by distinguishable photons (the $n = 3$ case is inset). The dynamically updated confidence that samples are drawn from the distribution of indistinguishable particles versus distinguishable particles reaches higher than 99.9%. (See Supplementary Materials for details).

In contrast to SBS, the GBS protocol does not project the input state onto a single Fock state. Rather, the input in GBS is an ensemble of single mode squeezed states, as shown in Fig. 1d, which further increases the n -photon detection probability as compared to SBS [25]. After processing with linear optical circuitry the probability for a particular pattern at single photon detectors is given by a function known as the Hafnian of the relevant transfer matrix. Similar to the permanent of a matrix, the Hafnian is computationally hard to calculate [25, 32, 33]. (See Supplementary Materials for details).

We implemented the GBS protocol using the two-colour pumping scheme described in Fig. 1b, which generates weak single-mode squeezed light at each source. While this spectral selection reduces the pump power below that of the single-colour configuration, we observed statistics with up to 4 signal photons at 1.1 Hz rate. The experimentally measured distribution for $n = 4$ photons,

with one photon per detector (full anti-bunching), shown in Fig. 3a, has a mean statistical fidelity of 87% with the ideal theoretical distribution. In validating GBS, a wide range of alternative models is available where output distributions arising from general Gaussian input states are classically tractable. As illustrated in Fig. 3b, we focus on models that are plausible in our experiment. We validate the ideal input state of 4 single-mode squeezed states against input with: thermal states, resulting from excessive loss; coherent states, from unfiltered pump light; distinguishable single-mode squeeze light, due to spectral mismatch; and two-mode squeezed states, from spurious photons generated at different wavelengths. For each test, a confidence $> 99.9\%$ is reached after ≈ 120 samples for an ideal model using single mode squeezed states rather than the alternative models. (See Supplementary Materials for details).

An application of GBS is the calculation of molecular vibronic spectra [6, 34, 35], where programmable linear optical circuitry, together with squeezed and displaced light, can approximate probabilities for the vibrational transition (Frank-Condon factors) between ground and excited states of a given molecule. To investigate the performance of silicon photonic chips for this application, we mapped our random walk circuit to a synthetic molecule and considered the difference $\mathcal{C} = F_Q - F_C$ between the fidelity of the reconstructed Franck-Condon (FC) profile F_Q and the optimal fidelity obtainable from a classical strategy F_C [34]. While the FC-profile directly reconstructed from GBS measurements has a fidelity $> 99\%$ to the ideal FC-profile, the low level of squeezing means that classically-tractable vacuum contributions dominate and the improvement over a classical strategy is small,

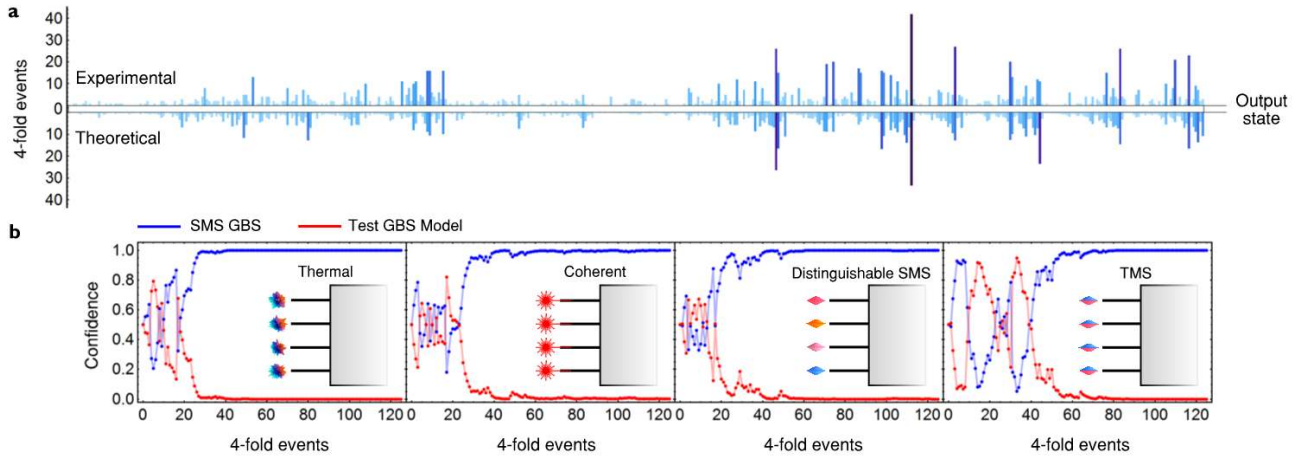


FIG. 3. Experimental results for GBS. (a) Experimental distribution for 4-photon events shows 87% fidelity with the theoretical distribution. The horizontal axis labels anti-bunched (one photon per detector) states in increasing order $\{(1, 2, 3, 4), (1, 2, 3, 5), \dots, (9, 10, 11, 12)\}$ from left to right. (b) Results of dynamic Bayesian model updating to validate that data is from the ideal GBS model of single mode squeezed states (SMS GBS, blue lines) against alternative (red lines) states, from left to right: thermal, coherent, distinguishable single-mode squeezed, and two-mode squeezed states.

($\mathcal{C} = 0.4\%$).

Data post-processing, based on characterised losses and detection efficiencies, makes it possible to investigate how the fidelity of the FC-profile depends on the amount of simulated squeezing, as shown in Fig. 4 (inset). For moderate levels of simulated squeezing, an improvement of up to $\mathcal{C} = 9\%$, corresponding to $F_Q = 86\%$ (shown in Fig. 4), is obtained from post-processing. For high values of simulated squeezing, due to the increased contribution of higher order photon terms, the approach does not provide any further advantage. (See Supplementary Materials for details).

Compared to SBS with 4 heralded photons, we ob-

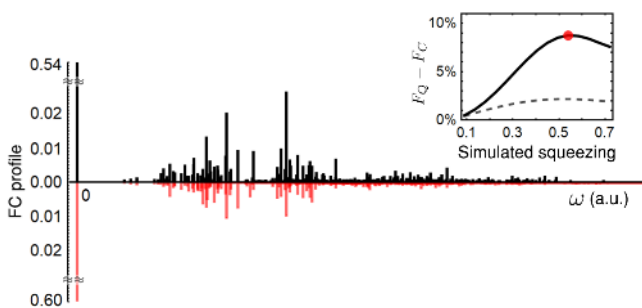


FIG. 4. Reconstructed FC-profile. Reconstructed FC-factors from GBS data (black) for frequencies ω are contrasted with theoretical estimates (red) for contributions of up to 8 photons (> 8 photon contributions are negligible). Inset is the improvement over optimal classical strategies in the fidelity of estimating the FC-profile, using simulated squeezing. The solid line plots cases that simulate squeezing by processing experimental data, while the dashed line indicates no post-processing. The red point indicates the specific FC-profile plotted in the main figure.

served much higher rates for 4-photon GBS using a pump with lower power, and requiring fewer detectors. This type of resource saving for GBS over SBS increases as the size of demonstration increases, though GBS requires approximately twice as many photons as SBS to demonstrate efficiency advantages over classical algorithms. Increasing the number and purity of integrated photon sources [36] while decreasing the loss in photonic circuitry to reduce noise and distinguishability among photons, leads to similar fidelities when considering the scaling of both the GBS and SBS protocols (e.g. loss acts to add noise via thermal components to the initial SBS-two-mode or GBS-single-mode squeezed state resource states). The maximum number of photons we generated and processed in these experiments is 8, which is double the largest reported to date in integrated photonics. Based on these results and further analyses (see Supplementary Materials), we estimate that arrays of several hundred integrated detectors, possible with current fabrication technologies [37], would allow fully-integrated experiments with tens of photons. In the context of calculating molecular transition probabilities, our class of photonic chip will be useful for reconstructing Franck-Condon profiles from photonic quantum sampling algorithms, if relevant instances requiring > 20 photon events are discovered. More generally, for problems that can be mapped to variant models of boson sampling, such as interrogating the vibrational dynamics of molecules [8], our results and analysis show that efficiency advantages over conventional computers are a realistic prospect with the platform of integrated photonics.

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