Chip-based single photon sources leverage the scalability and device integration afforded by modern semiconductor fabrication technology for quantum information processing applications \(^1\,2\). There are two dominant approaches to single photon generation at optical wavelengths. The first is through radiative decay of a single quantum emitter such as an atom or quantum dot that is "triggered" by excitation pulses. The second is through spontaneous photon pair production, in which the detection of one photon of the pair provides the time stamp by which the remaining ("heralded") single photon is identified. Both approaches for single photon generation were first demonstrated in bulk optical systems decades ago \(^3\,4\). Since then, chip-based triggered single photon sources based on systems such as a single quantum dot in a nanocavity \(^2\,6\,7\) have been widely studied, but this work is generally in cryogenically-cooled III-V semiconductor systems \(^8\). In contrast, photon pair production and subsequent heralded single photon generation, which are usually based on second- and third-order nonlinear processes that are achievable in a broader class of materials and at room temperature, have primarily been studied in larger systems such as bulk crystals \(^9\,10\), periodically-poled waveguides \(^11\,12\), and optical fibers \(^13\,16\). Recently, however, researchers have begun exploring four-wave-mixing (FWM) and photon pair production in CMOS-compatible silicon nanophotonic devices \(^17\,20\), which support a strong third-order optical nonlinearity and have the potential for significant levels of integration with other quantum optical components. Here, we build upon this work by demonstrating not only photon pair production, but also heralded single photon generation in a chip-based, silicon nanophotonic device operating in the telecommunications band and at room temperature.

Since silicon lacks a second-order optical nonlinearity, photon pair production uses the third-order (ultrafast Kerr) nonlinearity, typically in the degenerate four-wave-mixing configuration where a single pump beam at frequency \(\omega_p\) generates photons at signal (\(\omega_s\)) and idler (\(\omega_i\)) frequencies, with energy conservation requiring \(2\omega_p=\omega_s+\omega_i\) and momentum conservation (phasematching) being a requirement for appreciable pair production \(^21\). Silicon nanophotonic waveguides have an effective nonlinearity coefficient \(\gamma_{\text{eff}}\approx200 \text{ W}^{-1}\text{m}^{-1}\) that is four orders of magnitude larger than that of highly nonlinear optical fiber \(^17\,18\). Also, spontaneous Raman scattering, a broadband noise source in optical fibers that can require them to be cryogenically-cooled \(^22\), is generally less important in silicon, where it is narrowband and can thus be more easily avoided. On the other hand, in comparison to silica fibers, silicon devices exhibit two-photon absorption (TPA) and free-carrier absorption (FCA) at higher pump powers, incur coupling losses if photons have to be coupled to input/output optical fibers, and are generally limited to a few centimeters of waveguide length on a chip.

Our device geometry is a silicon coupled-resonator optical-waveguide (CROW) as shown in Fig. 1(a). The CROW consists of \(N = 35\) directly-coupled microring resonators (loss \(= 0.21 \text{ dB/ring}\)), such that each eigenmode is a collective resonance of all \(N\) resonators. Light is transmitted through the CROW in a disorder-tolerant slow light regime, with slowing factor \(S = c/v_g\) between 5 and 12, depending on the wavelength \((c\) is the speed of light and \(v_g\) is the group velocity). As \(\gamma_{\text{eff}}\) is enhanced by a factor \(S^2\), the CROW achieves higher levels of conversion within the limited footprint available on a chip. Indeed, in ref. \(^23\), we have shown classical FWM with \(\gamma_{\text{eff}} \approx 4100 \text{ W}^{-1}\text{m}^{-1}\), representing +16 dB en-
enhanced conversion compared to a conventional nanophotonic waveguide, for over > 10 THz (80 nm) separation between signal and idler. This and other reports of FWM in CROWs [24] have shown similar conversion efficiencies to the best photonic crystal waveguides (PCWGs). However, such widely-separated wavelengths, which span a significant fraction of the fiber-optic telecommunications window, are difficult to achieve in PCWGs because of the limited bandwidth of their slow-light regime compared to CROWs; ≈1.25 THz (10 nm) signal-idler separation was reported in ref. [21].

We first show photon pair production from the Si CROW device, using the experimental setup depicted in Fig. 1(b). Time-correlated signal and idler photons are expected to be generated in multiple pairs of CROW transmission bands that are approximately equally red- and blue-detuned from our amplified pump beam at 1549.6 nm, as demonstrated in previous classical FWM mixing experiments [23]. We choose a signal-idler pair at 1529.5 nm and 1570.5 nm, as shown in Fig. 1(c). Here, to show the classical FWM process, a strong pump at 1549.6 nm was combined with a probe field at 1570.5 nm, resulting in the addition of stimulated photons into the 1570.5 nm field and generation of a new field at 1529.5 nm. For spontaneous FWM (SFWM) experiments, the 1570.5 nm probe field was disconnected so that spontaneous photons are generated in the signal and idler bands. The 1549.6 nm pump was filtered to a 1.0 nm bandwidth through cascaded WDM and tunable filters, and light was coupled to and from the chip (loss = 5 dB per coupler) using tapered lensed fibers and polymeric overlaid waveguide couplers. Output light from the chip was filtered by a set of WDM pump-rejection filters (120 dB estimated pump rejection at 1550 nm ± 3 nm) and then routed through cascaded C- and L-band WDM filters (estimated 150 dB pump isolation; 0.5 nm bandwidth) to spectrally separate and isolate the signal and idler photons, respectively. The signal (C-band) and idler (L-band) photons were detected by InGaAs/InP Single-Photon Avalanche Diodes (SPADs) [25] gated electronically at 1 MHz (10 % detection efficiency, 20 ns gate width, and 10 µs dead-time), and raw coincidences (Craw) and accidentals (Araw) were measured by a time-correlated single photon counting (TCSPC) system operating with 512 ps timing resolution, with typical measurement integration times between 1800 s and 5400 s. Coincidences due to dark counts (D) were measured separately for both integration times at each detector, and subtracted to yield C = Craw − Araw and A = Araw − D, with the coincidence-to-accidental ratio given as CAR = C/A [24].

CAR under continuous wave (cw) excitation is shown in Fig. 1(d) as a function of the input power into the CROW. CAR initially increased and then rolled off at higher intensities, which is the anticipated behavior based on other studies [17 20], where at low powers CAR is thought to be limited by detector noise, while at higher powers, nonlinear loss and multiple pair generation are
FIG. 2. Heralded single photon measurement. (a) Schematic of the experimental setup used to perform heralded single photon measurements. The Si CROW waveguide is pumped by a pulsed 1549.6 nm laser (2.5 ns pulses, 8 MHz repetition rate) generated by a modulated and amplified diode laser. Generated photon pairs are spectrally isolated and separated into the C-band (1529.5 nm) and L-band (1570.5 nm). Detection of an L-band photon by an InGaAs/InP SPAD is used to trigger a Hanbury-Brown and Twiss photon correlation measurement on the C-band photon. (b) Heralded $g^{(2)}(0)$ as a function of average power at the CROW input [30]. (c) Heralding rate at the CROW output as a function of average power at the CROW input. Results are plotted in units of (left y-axis) heralding photons per second and (right y-axis) heralding photons per pulse.

The limiting factors. Peak CAR was 10.4 ± 1.4 at an input power of 12 dBm, which was below the level for 1 dB excess nonlinear absorption in these CROWs [23]. In Fig. 1(c), we plot the coincidence and accidental rates at the output of the CROW [27]. At peak CAR, the coincidence rate is $\approx 1.5 \times 10^{-3}$ per detector gate; considering the cw pumping and the 1 MHz detector trigger rate and 20 ns gate width, this corresponds to a pair coincidence rate of $\approx 73$ kHz. Figure 1(e) also shows quadratic fits (solid lines) to the six lowest power data points; the sub-quadratic dependence of $\alpha$ and $\beta$ as a function of average input power into the CROW.

In Fig. 2(b), we plot the value of $g^{(2)}(0)$ as a function of average input power into the CROW. $g^{(2)}(0) < 0.5$ for all pump powers that we recorded, indicating that we indeed have a source that is antibunched and dominantly composed of single photons [31]. The minimum value we measured is $g^{(2)}(0) = 0.19 \pm 0.03$ at $\approx 1.7$ mW of average power into the CROW. At lower power levels in our experiment, $g^{(2)}(0)$ may be limited by detector dark counts, while at higher power levels, the increase in $g^{(2)}(0)$ is likely due to the increased multi-photon prob-
ability as multiple photon pairs are generated in each optical pulse. The maximum power levels we can inject into the CROW were ultimately limited by the damage threshold of the input couplers. In Fig. 2c), we plot the heralding rate (detection rate of L-band photons by SPAD A) at the CROW output. At the minimum value of $g^{(2)}(0)$, the heralding rate was $\approx 220$ kHz $\approx 0.028$ photons/pulse. As the input power to the CROW increases, the generation rate of heralding photons saturated near 1 MHz due to TPA/FCA effects in silicon. Under pulsed pumping (2.5 ns pulses, 8 MHz trigger rate) and at the input power corresponding to the minimum value of $g^{(2)}(0)$, CAR$\approx 15$ was measured without dark count subtraction. Subtraction of dark count coincidences (due to dark counts on both detectors as well dark counts on one detector and photon detection events on the other detector) yields CAR$=23.8 \pm 5.6$. This significant correction indicates that $g^{(2)}(0)$ reported in Fig. 2 may contain a large contribution due to dark counts.

In summary, we have demonstrated a telecommunications-band silicon heralded single photon source. Spontaneous four-wave-mixing in a 35-ring silicon coupled resonator optical waveguide generated photon pairs spaced by 40 nm, with a coincidence-to-accidental ratio $> 10$ for continuous wave pumping and $> 20$ for pulsed pumping. Three InGaAs/InP single photon counters were used to perform a measurement in which the detection of the idler photons from the pairs triggers a photon correlation measurement on the corresponding signal photons. We measured antibunching with $g^{(2)}(0)=0.19 \pm 0.03$, indicating a source that is dominantly composed of single photons. Our demonstration of heralded single photon generation within a silicon photonics platform, for which sophisticated levels of switching and multiplexing have been shown \cite{31}, is a step towards integration of multiple heralded sources to create quasi-deterministic single photon sources \cite{32,33} that may then be combined with waveguide quantum photonic circuits \cite{35} and single photon counters \cite{36} to achieve high levels of functionality in future quantum information processing applications.

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in the same way. The uncertainties in $A_{\text{raw}}$ and $D$ are one standard deviation values and are propagated to generate the error bars in the CAR plot.

[27] Coincidence and accidental rates at the CROW output are determined by taking the measured values and accounting for detector efficiency, filter losses, and output coupling loss from the CROW into the lensed fiber.

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