have integrated the full coincidence histogram peak to obtain the *CC* values in Eq. (4) for low input powers (<2.1mW) in the on-resonance case. The channel collection efficiencies are found to be −27 dB and −34 dB for channel 1 and channel 2 respectively, and take into account all losses within the system (including device coupling losses). These values are used in the calculation of the pair generation rate throughout the experiments.

3.2 Calculation of the CAR

The CAR is calculated by acquiring a histogram of the coincidence counts within an 8 ps detection time interval between signal and idler photons. As already discussed, Figs. 3(a)–3(c) show examples of three coincidence histograms for three different input powers. The CC is defined as the sum of the counts within the given coincidence window. The accidentals are directly measured by integrating the events outside the coincidence peak. By averaging the number of events in each bin outside the coincidence peak and multiplying by the number of bins in one coincidence window, we obtain the number of accidentals. The CAR value and associated CC depends greatly on the duration of the defined coincidence window. Figures 3(d)–3(f) plot this dependence of the CAR and CC on the duration of the chosen coincidence window, calculated using the corresponding histograms in Figs. 3(a)–3(c) respectively. The curves with error-bars in Figs. 3(d)–3(f) show the measured CAR values, and the dashed red curves correspond to CAR values calculated using a Gaussian fit to the histograms in Figs. 3(a)–3(c). As the coincidence window gets wider the values of CAR have a decreasing trend, while the CC saturates at around 2xFWHM. To define a single value of CAR and photon pair generation rate we have used the coincidence window width corresponding to the FWHM of the histograms in Figs. 3(a)–3(c), which is ~230 ps in all cases and is shown as a dotted vertical black line in Figs. 3(d)–3(f).

It can be observed that as the coincidence window duration approaches zero, the CAR values calculated from the Gaussian fit tend to a single value. This value represents that maximum obtainable CAR value from this particular experiment, taking into account all the noise sources including detector dark counts, pump leakage, Raman noise, multi-pair production, etc. It should be noted that the detector dark count rate of 1 kHz, overall collection efficiencies of −27 dB and −34 dB and a coincidence window of 230 ps yield an upper limit on the CAR value of 830. The total coincidence count rate on the other hand tends to a maximum value as the coincidence window duration tends to infinity (and approaches zero as the coincidence window duration tends to zero). Thus to define single values for the photon pair generation rate and CAR, it is necessary to choose a particular coincidence window duration. Typically, the pair generation rates and CAR values quoted in the literature use a range of different and some-what arbitrarily chosen values of the coincidence window. To define the single values for pair generation rate and CAR presented in Fig. 2, we have chosen a coincidence window duration defined as the FWHM of the Gaussian fit to the coincidence peak (the width of the peak is determined by the combined jitter in the single photon detectors, amplifiers and timer interval analyzer and is 230 ps). This enables a useful estimate of the pair generation rate and CAR values by taking into account a significant number of all the coincidence events, yielding values that are close to the maximum obtainable pair generation rates (given as $T \rightarrow$ infinity) and the maximum obtainable CAR (given as $T \rightarrow 0$). It thus provides a useful benchmark for comparison with previous experimental results (see Table 1). Table 2 presents a summary of the photon-pair generation rate and associated CAR for two different coincidence windows; one covering FWHM (~230 ps) and one covering ± 3 standard deviations (~580 ps) of the Gaussian fit to the coincidence histogram.

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Table 2. Tabulate results of the CAR and pair generation rate for coincidence window durations covering FWHM and ± 3 standard deviations of the Gaussian fit to the coincidence histogram.

Injection power	CAR (FWHM)	CAR (± 3σ)	Pair generation rate (FWHM)	Pair generation rate (± 3σ)
With 8V reverse bias				
4.8 mW	37 ± 1.3	19 ± 0.6	123 MHz	161 MHz
No reverse bias				
4.8 mW	43 ± 2.2	23 ± 1	59 MHz	75 MHz
1.1 mW	359 ± 16	125 ± 3	2.7 MHz	6 MHz
0.019 mW	602 ± 37	315 ± 18	827 kHz	1 MHz

4. Discussion

In this letter we have studied photon pair generation in a silicon micro-ring resonator through SFWM. A maximum CAR value of 602 ± 37 is measured for an injection pump power of 0.019 mW, corresponding to photon-pair generation rate of 827 kHz. The maximum photon pair generation rate of 123 MHz is achieved, at an injection pump power of 4.8 mW, by applying a 8 V reverse bias voltage across the p-i-n structure to mitigate the parasitic effects of free-carrier absorption (with an associated CAR value of 37 ± 1.3). Increasing the reverse bias voltage beyond 8 V does not lead to a further increase in the photon pair generation rate, and we instead observe a reduction in this rate. We attribute this effect to a change in the coupling constant between the ring resonator and the bus through thermo-optic effects induced by the removal of the free carriers. As we increased the bias voltage, we indeed observed a shift in the resonance peak towards longer wavelengths jointly due to the dominant thermo-optic effect and a reduction in the free carrier dispersion. These free-carrier absorption parasitic effects are even more prominent for devices pumped with short laser pulses. For instance, Xiong et al [11] investigated pair generation in slow-light photonic crystal structures, and demonstrated clear saturation due to TPA and FCA at peak power of just 0.4W. Implementation of a p-i-n structure in such a device could extend the operation of these devices into a regime of higher pair generation rate.

While the photon pair rate increases with reverse bias, it is worth noting that the CAR is only slightly degraded. This degradation is expected from the increase of multi-pair terms due to the higher pair generation rate. However this effect was mitigated by an increase in the signal-idler collection due to the reduced FCA.

The results presented in this paper highlight the potential of silicon as a promising photon source for photonic quantum information processing and communications, with properties of low noise (suitable for example in high fidelity quantum operations) or high generation rate (suitable for example in high-rate quantum key distribution). It is interesting to note from comparing the CAR values shown in Fig. 2(b), we see that for the on-resonance conditions, the reverse-biased and un-biased case give similar values, whereas for off-resonance the CAR is much lower. This is likely due to noise from Raman scattering in optical fibers of the experimental setup which deteriorates the CAR for low photon-pair generation rates in the off-resonance case.

Currently the filtering of the pump, signal and idler photons are achieved using fiber optic components, but with improved architectures, on-chip filtering could also be performed by further taking advantage of resonant structures. The ring cavity also has the advantage of generating photon pairs having low spectral entanglement [21] when pumped with a pulsed source having a bandwidth greater than the resonance width. This will enable such ring sources to be used as high purity single photon sources, heralded on the measurement of one of the photon pairs. The relevant figures of merit (CAR and CC) for such a source should be taken by integrating the full coincidence peak (at least at ± 3σ) since selecting part of the peak would be equivalent to a loss on the heralded photon generated thus lowering the heralding efficiency of the source. The high CAR achieved makes these sources a good candidate for low noise multiplexed single photon sources [22] which could in turn be used in a scalable manner to seed a linear optical quantum circuit.

The on-chip photon pair source reported in this paper is fully compatible with already demonstrated silicon quantum circuits [9] and high-efficiency waveguide integrated superconducting single-photon detectors [7,8]. It is therefore possible to realize in a single material system all the major components required for on-chip linear optics quantum information processing; low noise single photon sources, compact waveguide circuits and efficient single photon detectors. The next major challenge is to integrate all these components into a single unified technology platform, for which the silicon-on-insulator material system appears to be a promising candidate.

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