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Scalable feedback control of single photon sources for photonic quantum technologies: supplementary material

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A. DEVICE DETAILS

The device, shown in Fig. 2(a), is fabricated in a standard CMOS silicon photonics process and consists of two microring resonators for photon generation with radius $R = 11$ μm, coupled to a 500 nm wide $\times$ 220 nm silicon bus waveguide. Each ring has a Q factor of 2.5×10^4, and a free spectral range FSR $= 8.8$ nm. After just 40 μm the bus waveguide is coupled to a demultiplexing ring ($R = 8$ μm, FSR$=$ 12 nm) to separate single photons and pump light, and photons via the drop port are routed to a phase shifter and directional coupler for state engineering. All four rings are thermo-optically controlled by embedded resistive heaters formed by doped silicon regions contacting the metal interconnect layer. To minimize losses due to free-carrier absorption, a low dopant concentration in the waveguide region overlapping with the optical mode is employed. The combination of both generation and demultiplexing rings enables a pump suppression of 37 dB, mitigating further incoherent photon generation within the bus waveguide. The experimental setup shown in Fig. S1 consists of two tuneable telecom lasers set to $\lambda_{p_1} = 1582.3$ nm and $\lambda_{p_2} = 1547.7$ nm, at $+2$ and -2 FSR of the tuned generation rings, for degenerate pair photon generation at $\lambda_{s,i} = 1565.0$ nm. Pump lasers are passed through fibre-optic tuneable band pass filters (BPF) which provides a total of 100 dB suppression of unwanted sidebands occurring due to amplified spontaneous emission.

Laser light is edge coupled into the chip via custom built SiN interposers, which reduces the optical mode field diameter to better match the on-chip tapered mode convertor, achieving an estimated loss per facet of -2.5 ± 0.5 dB. The device is mounted on top of a Peltier cooling unit to maintain thermal stability, and the thermo-optic phase shifters are controlled by a custom-built multi-channel digital to analogue converter (DAC) which provides 16-bits voltage precision. Both correlated photons and pump light are out-coupled and passed through a switch which either connects directly to a photodiode (PD) array or narrow linewidth filters (bulk interference filter connected to a fibre-coupled U-bench), which along with on-chip filtering, provides a total pump suppression of ~ 100 dB. Photons are sent to two superconducting nanowire single photon detectors (SNSPD) with quantum efficiencies of $\eta = 75$ %, and the signals are time-tagged using a time-correlated single photon counting (TCSPC) module.

B. THEORETICAL COUPLED RING MODEL

By modeling the transmission of coupled microring resonators, we can show that there is one and only one possible generation ring voltage combination that leads to a minimum in the rings' combined transmitted power, and hence there are no local minima that the Nelder-Mead search algorithm could potentially converge to. The transmission function of a single ring can be taken to be a Lorentzian:

$$T(\lambda) = \frac{-0.5\Gamma}{(\lambda - \lambda_{las})^2 + (0.5\Gamma)^2} \tag{S1}$$

where Γ and λ_{las} are the width parameter and laser wavelength respectively. The dependence of the rings' central wavelengths

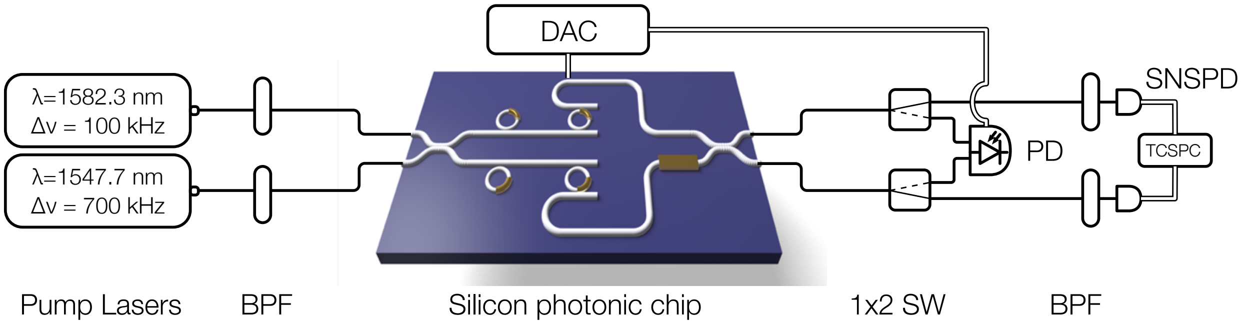

Fig. S1. Experimental setup. A schematic of the experimental setup with solid lines referring to fibre optic components and double lines refer to electrical connections. Two tunable lasers are passed through a bandpass filter (BPF) which then pump the silicon photonic chip. The output passes through a 1×2 switch (SW) which connects either to photodiode array (PD) or superconducting nanowire single photon detectors (SNSPD) and time-correlated single photon counting (TCSPC) module. On-chip thermo-optic phase shifters are controlled by a multi-channel digital to analogue converter (DAC).

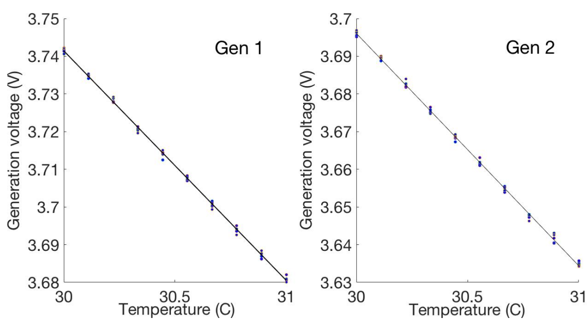

Fig. S2. Temperature tuning. Five sets of temperature-voltage data points for each generation ring alongside a linear fit.

(λ_1 and λ_2) on ring voltages can be modelled as

$$\lambda_1 = \lambda_{01} + \gamma_1 V_1^2 + \alpha_{12} V_2^2 \quad \text{(S2)}$$
$$\lambda_2 = \lambda_{02} + \gamma_2 V_2^2 + \alpha_{12} V_1^2 \quad \text{(S3)}$$

where λ_{01} and λ_{02} are the central resonances of the rings with no applied voltage tuning, coefficients γ_1 and γ_2 correspond to the strength of the rings' wavelength dependence on voltage applied to themselves, and the coefficient α_{12} corresponds to the strength of the each ring's wavelength dependence on voltage applied to the other. The voltage-squared dependence of the central wavelength on voltage arises from linearity of the wavelength shift with temperature, and hence with the dissipated power. In a physically realistic case, both the ratios $\frac{\gamma_1}{\alpha_{12}}$ and $\frac{\gamma_2}{\alpha_{12}}$ will be much greater than both $\frac{\lambda_{las}-\lambda_{01}}{\lambda_{las}-\lambda_{02}}$ and $\frac{\lambda_{las}-\lambda_{02}}{\lambda_{las}-\lambda_{01}}$. The total transmission of two rings in series is given as:

$$T(\lambda_1, \lambda_2) = \frac{-0.5\Gamma}{(\lambda_1 - \lambda_{las})^2 + (0.5\Gamma)^2} * \frac{-0.5\Gamma}{(\lambda_2 - \lambda_{las})^2 + (0.5\Gamma)^2} \quad \text{(S4)}$$

and the total transmission in parallel as:

$$T(\lambda_1, \lambda_2) = \frac{-0.5\Gamma}{(\lambda_1 - \lambda_{las})^2 + (0.5\Gamma)^2} + \frac{-0.5\Gamma}{(\lambda_2 - \lambda_{las})^2 + (0.5\Gamma)^2}. \quad \text{(S5)}$$

Both the series and parallel transmission functions have critical points where the conditions $\frac{\partial T}{\partial \lambda_1} = 0$ and $\frac{\partial T}{\partial \lambda_2} = 0$ hold. In order to satisfy both conditions, we require $V_1 = 0$ or $\lambda_1 = \lambda_{01} + \gamma_1 V_1^2 + \alpha_{12} V_2^2 = \lambda_{las}$, and $V_2 = 0$ or $\lambda_1 = \lambda_{01} + \gamma_1 V_1^2 + \alpha_{12} V_2^2 = \lambda_{las}$. Out of the four possible combinations, only one gives a minimum (the others are a maximum and saddle points):

$$\lambda_1 = \lambda_{01} + \gamma_1 V_1^2 + \alpha_{12} V_2^2 = \lambda_{las} \quad \text{(S6)}$$
$$\lambda_2 = \lambda_{02} + \gamma_2 V_2^2 + \alpha_{12} V_1^2 = \lambda_{las} \quad \text{(S7)}$$

Given the physically realistic stipulations on γ_1, γ_2, α_{12}, $\lambda_{las} - \lambda_{01}$ and $\lambda_{las} - \lambda_{02}$, the two equations above are guaranteed to have a solution with non-zero values of V_1 and V_2, which corresponds to tuning both rings to the laser wavelength. Hence, there is only one global minimum value of the transmission function for non-negative voltages, and no local minima. This guarantees that if our search converges, it will have converged to the true global minimum. This model may be generalised to an arbitrary number of ring resonators in series or parallel, such that the total transmission of N rings in series will be given by

$$T(\lambda_1, \lambda_2, \cdots, \lambda_N) = \prod_{i=1}^{N} \frac{-0.5\Gamma}{(\lambda_i - \lambda_{las})^2 + (0.5\Gamma)^2} \quad \text{(S8)}$$

and the total transmission in parallel by

$$T(\lambda_1, \lambda_2, \cdots, \lambda_N) = \sum_{i=1}^{N} \frac{-0.5\Gamma}{(\lambda_i - \lambda_{las})^2 + (0.5\Gamma)^2} \quad \text{(S9)}$$

As in the two-ring case above, the sole minimum of the transmission function is achieved when all rings are individually tuned to the laser wavelength, and there are no local minima.

C. TUNING CURVES

By sweeping the temperature, T, from 30 to 31 degrees and iteratively aligning the rings at each voltage using the Nelder-Mead algorithm, we obtain generation ring voltage (V_1 and V_2) versus temperature data (Fig S2). Based on 5 such sweeps, we

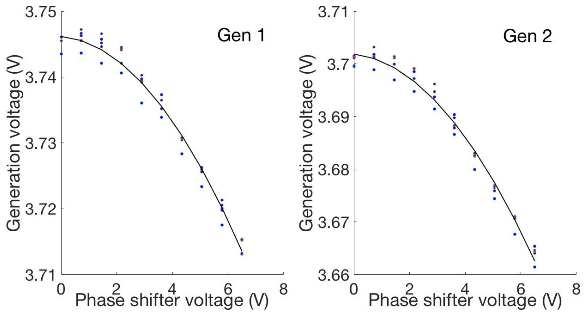

Fig. S3. Phase voltage tuning. Five sets of Phase shifter-voltage data points for each generation ring alongside a quadratic fit.

obtain the following best-fit linear model for the dependence of the ring voltages on temperature:

$$V_1(T) = -0.06090T + 5.568 \tag{S10}$$
$$V_2(T) = -0.06166T + 5.546 \tag{S11}$$

Similarly, by sweeping the phase shifter voltage, V_p, from 0 to 6.5 volts and aligning the rings at each voltage using the Nelder-Mead algorithm, we obtain ring voltage versus phase shifter voltage data (Fig S3). Based on 5 sweeps, we obtain a best-fit quadratic model for the dependence of the ring voltages on the phase shifter voltage:

$$V_1(V_p) = -0.0007192V_p^2 - 0.0003439V_p + 3.746 \tag{S12}$$
$$V_2(V_p) = -0.0008414V_p^2 - 0.000576V_p + 3.702 \tag{S13}$$