# Toward quantum electronic-photonic systems-on-chip: a monolithic source of quantum-correlated photons with integrated frequency locking electronics and pump rejection

I. Wang[1,†,*], J.M. Fargas Cabanillas[1,*], D. Kramnik[2,*], A. Ramesh[3,*], S. Buchbinder[2], P. Kumar[3], V. Stojanović[2] and M.A. Popović[1,‡]

[1] *Department of Electrical and Computer Engineering, Photonics Center, Boston University, Boston, MA 02215, USA*
[2] *Department of Electrical Engineering and Computer Science, UC Berkeley, Berkeley, CA 94720, USA*
[3] *Center for Photonic Communication and Computing, Dept. of Electrical and Computer Eng., Northwestern University, Evanston, IL 60208, USA*
[†] *imbert@bu.edu*, [‡] *mpopovic@bu.edu*, [*] *These authors contributed equally*

**Abstract:** We demonstrate a CMOS electronic-photonic photon-pair source with integrated feedback-controlled frequency locking, >80 dB on-chip pump rejection, and signal/idler demultiplexing, achieving a CAR of ≃5 at ≃40 ccps pair rate. 

Arrays of stochastic photon-pair generators based on spontaneous four-wave mixing (SFWM) are a key component of many proposed optical quantum computing and quantum networking architectures [1]. An example is multi-pulsed arrays of stochastic generators to produce a more deterministic photon-pair source. Two key challenges in scaling toward a large quantum system-on-chip (QSoC) with many sources are to maintain the same wavelength for each pair source—necessary for preventing quantum decoherence and qubit errors—and to isolate the photon pairs from the strong classical pump light. Pair sources with either frequency locking or high-extinction pump filters have been demonstrated previously [2–4], but not simultaneously on the same chip. Nor has on-chip electronics been used to produce modular units for scalable QSoCs. In this work, *we demonstrate the first electronic-photonic quantum system-on-chip (EPQSoC)*. This EPQSoC is aimed toward the function of a self-contained, "wall-plug" photon-pair source on chip. Our eventual goal is for this device to accept only DC electrical power and CW pump-laser light ("optical power") and output quantum-correlated photon pairs. The work presented here enables a SFWM photon-pair source which combines feedback-controlled frequency locking, high extinction (>80 dB) on-chip pump filtering, and signal/idler demultiplexing with circuits implemented alongside photonics in a 45 nm SOI CMOS platform (GlobalFoundries 45RFSOI) in which large-scale electronic-photonic circuits have previously been demonstrated (e.g. [5]).

Fig. 1(a) shows a to-scale layout of our photon-pair source. Pump light from a CW input laser is coupled to the system with a low-loss (<3 dB) grating coupler (GC). It then passes through a tunable second-order microring on-chip filter, which spectrally filters out the amplified spontaneous emission (ASE) accompanying the pump in the signal/idler bands by >40 dB. The filtered pump is then strongly coupled to a tunable microring cavity with an intrinsic (extrinsic) $Q$ of 79,000 (50,000), which generates the photon pairs via SFWM. The inner wall of the microring has Si contact spokes with alternating p- and n-type doping, creating an azimuthally periodic p-i-n diode which sweeps out free carriers under reverse bias, enabling photocarrier sensing and damping the free-carrier absorption induced thermo-optical oscillations [6]. The light that propagates in the bus after the source cavity is predominantly pump photons

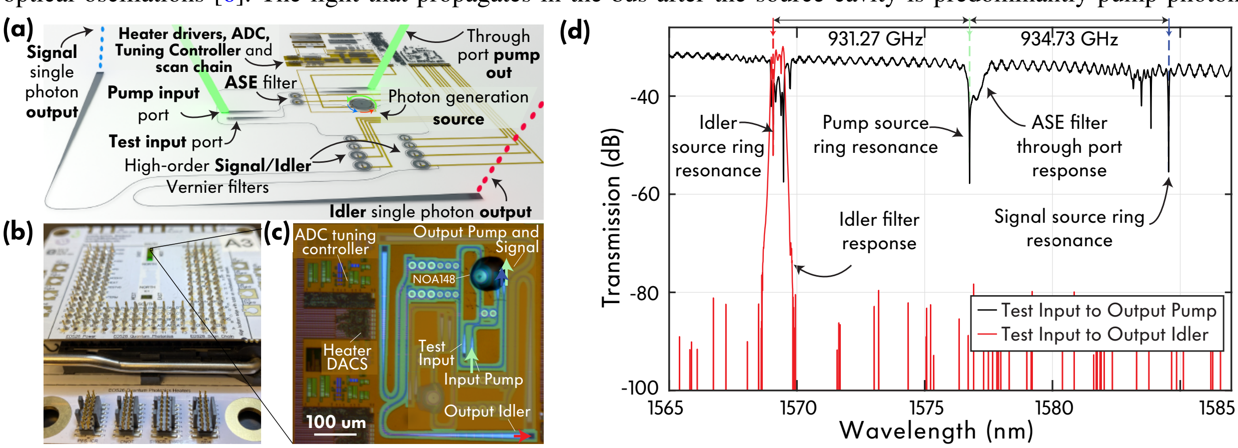


Fig. 1: (a) EPQSoC schematic. (b) CMOS package with chip carrier and host board. (c) EPQSoC micrograph. The source ring has only 1 nm tuning range due to a layout error. We used Norland Optical Adhesive (NOA148) to bias shift its resonance by 3 nm. Future heater designs will have a full FSR tuning range. (d) Idler output port and through port transmission from test input port.

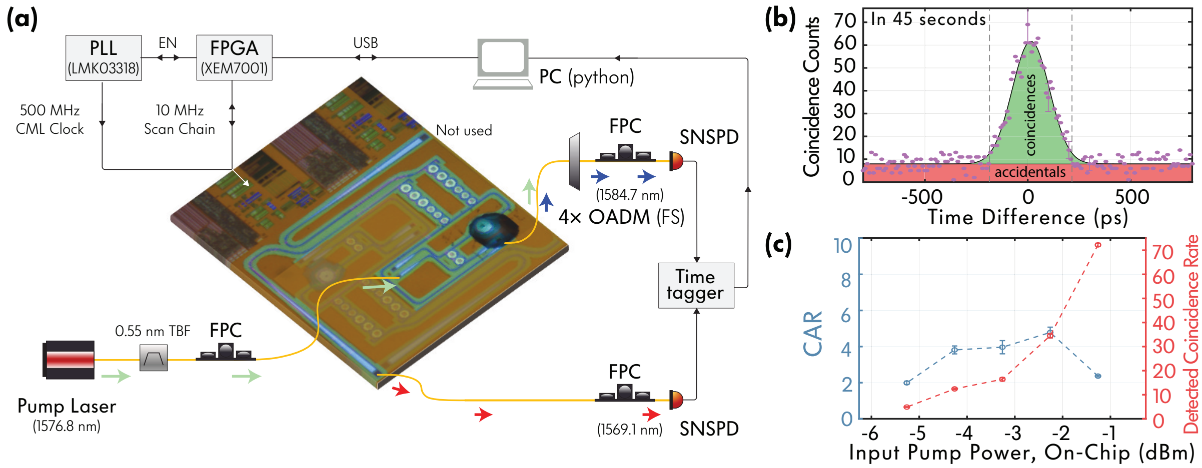


Fig. 2: (a) Experimental setup for measuring CAR and coincidence count rates using superconducting nanowire single photon detectors (SNSPDs). The off-chip tunable bandpass filter (TBF) provides additional ASE filtering, necessary because of the off-chip OADM's 13nm passband. (b) Coincidence histogram with 10 ps bin widths integrated for 45 seconds at an on-chip power of −2.3 dBm. (c) CAR and detected coincidence-pair count rate as a function of pump power on chip. The represented uncertainties are estimated from Poisson statistics, but additional sources of systematic error such as alignment stability are not quantified.

intermixed with a sparse stream of SFWM-generated signal/idler photon pairs. The bus waveguide then feeds two parallel $6^{th}$-order tunable channel add-drop filters, with 60 GHz 3 dB-bandwidth, $<$1 dB measured insertion loss, and $>$80 dB measured extinction ratio (limited by our power sensor sensitivity, $\approx$160 dB simulated) [7], which route the signal and idler photons to respective GCs. The two filters are designed to drop the signal and idler photons from the input, while rejecting the pump photons and allowing to demultiplex them on chip, isolated from the pump light and other noises. To avoid possible leakage of generated Raman through adjacent FSRs, the filters are designed with a Vernier-scheme to increase their effective FSR to 6.7 THz. Fig. 2 (a) shows the experimental setup for characterizing the photon-pair generation rate and coincidence-to-accidentals ratio (CAR). The source is locked using closed-loop feedback control to the wavelength of the pump, and one on-chip filter is thermally tuned to the idler wavelength. In principle, the other on-chip filter is designed to be tuned to the signal wavelength, but in this chip the tuning range of the filter was insufficient to align to the signal wavelength due to a design bug (missing nominal wavelength offset). This can be trivially corrected in future designs by adjusting the nominal radius of the filter rings of the two respective filters. For the purpose of this demonstration, light exiting the chip via the through-port GC, carrying the pump and signal only, is routed to off-chip optical add-drop multiplexers (OADMs) centered at 1590 nm which pass the signal photons while attenuating the pump light by $>$120 dB with a 13 nm passband en route to SNSPDs with 60 % detection efficiency. Fig. 2 (b) shows an example histogram and Gaussian fit used to extract the CAR and coincidence rate and Fig. 2 (c) shows the trends with respect to pump power. We chose a $\pm 2\sigma$ coincidence window of 400 ps to define the CAR and pair-generation rate, yielding a maximum CAR of $4.8 \pm 0.3$ at $-2.3$ dBm power on chip and maximum coincidence rate of $72 \pm 1$ coincidence counts per second at $-1.6$ dBm power on chip.

Our proof-of-concept implementation demonstrates the feasibility of EPQSoCs such as a fully integrated, scalable on-chip entangled photon-pair source, which could facilitate array-heralded single photon sources with multiplexed quasi-deterministic designs, enabled by electronic-photonic integration. While here, the signal channel is filtered off-chip to reject the pump, we note that the pair-rate and CAR are limited by the channel with off-chip filtering, which is both lossier (due to the off-chip filter insertion loss) and noisier (wider filter passband). This suggests that future iterations of this system, with the remaining on-chip filter tuned to the signal wavelength, will have improved performance.

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## References


1. Rudolph, T. "Why I am optimistic about the silicon-photonic route to quantum computing", APL Photonics. 2, 030901 (2017).
2. C. Gentry, *et al.* "Monolithic Source of Entangled Photons with Integrated Pump Rejection", CLEO, paper JTh4C.3 (2018).
3. J. Fargas-Cabanillas, D. Kramnik, A. Ramesh, *et al.*, "Tunable Source of Quantum-Correlated Photons with Integrated Pump...", FiO (2021).
4. Carolan, J. *et al.*, "Scalable feedback control of single photon sources for photonic quantum technologies", Optica 6, 335-340 (2019).
5. C. Sun, M.T. Wade, Y. Lee, *et al.* "Single-chip microprocessor that communicates directly using light", Nature 528, 534–538 (2015).
6. D. Kramnik, *et al.* "Monolithically Integrated Feedback Control of Photon-Pair Generation by a Nonlinear...", CLEO, *submitted* (2022).
7. Fargas Cabanillas, J. M. *et al.*, "Monolithically Integrated High-Order Vernier Filters for Electronic-Photonic...", CLEO *submitted* (2022).