Photon Pair Generation Using Silicon Photonic Microring and Hybrid Laser
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Abstract: Using all silicon photonic components, including an electrically-pumped hybrid silicon laser and a high-Q ring resonator, photon pairs with non-classical correlations were generated at room temperature near 1310 nm wavelengths.

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Deployment of quantum optical communication in short-distance optical networks, such as data centers, may be achieved by using compact and inexpensive silicon microchips to generate photons; and it has been shown that integrating microelectronic components such as p-i-n diodes can stabilize against temperature fluctuations [1] and replace mode-locked lasers for pulse carving [2]. Silicon photonic technology has been used for low-power optically-pumped pair and heralded single photon generation [1], gates [2], and detection [3]; with the missing device within the quantum silicon photonics toolkit being the on-chip integration of the pump-laser. Here, we demonstrate room-temperature pair generation using electrically-pumped hybrid silicon lasers and silicon microring resonators.

Our experimental setup is shown in Fig. 1. Spontaneous four-wave mixing near wavelengths of 1.31 µm (widely used in short-range optical communications) was initiated in silicon microring resonators using light from the silicon photonic hybrid laser. The microring was fabricated using a foundry process on standard silicon-on-insulator (SOI) wafers with 2 µm buried oxide thickness, and a p-i-n diode was incorporated within the microring to monitor the reverse-biased photocurrent for stabilization [1]. The loaded Q-factor was $Q_L = 1.1 \times 10^5$ at 1307 nm. The hybrid silicon laser was created by wafer bonding technology and processed in a CMOS fab [6, 7]. The laser was operated using a laser diode controller in constant-current mode. A bandpass filter with 6 nm bandwidth was used to partially filter the broadband amplified spontaneous emission from the hybrid laser by more than 60 dB. We tested pair generation when the laser and the microring chips were separately stabilized and aligned using off-the-shelf thermoelectric controllers (TECs) between about 20°C and 65°C; and/or the laser current. Light was coupled to and from the chip (loss 3.5 dB/coupler) using lensed tapered SMF-28 fibers. Output light from the chip was split by a wavelength-insensitive 3-dB splitter and routed through cascaded filters to select one pair of spectral lines of Stokes and anti-Stokes photons positioned symmetrically around the pump wavelength. The filters provided more than 120 dB passband-stopband contrast, and 1.8 nm bandwidth, with 5.4 dB and 6.4 dB insertion loss in the two cascaded channels. We tested pair generation at one and two free-spectral ranges removed from the pump.

The coincidence-to-accidentals ratio (CAR) was measured using InGaAs single-photon avalanche detectors (SPADs) gated electronically at 50 MHz (15% detection efficiency, 2.5 ns gate width, and 10 µs holdoff), and coincidences

Fig. 1a. A hybrid silicon photonic laser was electrically injected using a laser diode controller (LDC) to generate pump light for pair generation through spontaneous four-wave mixing near 1310 nm in a silicon photonic microring resonator at room temperature. Non-classical coincidences were measured between the filtered Stokes and anti-Stokes photons using gated InGaAs SPADs (without cryogenic cooling) and time-correlated single photon counting (TCSPC). b, Normalized transmission spectrum of the microring and the laser, with linewidths approx. 2 GHz and < 1 MHz, respectively.
were measured by a time-correlated single photon counting (TCSPC) system. Whereas cryogenically-cooled superconducting detectors offer superior performance, thermoelectrically-cooled (233K) InGaAs SPADs are more likely to be used in data networks. Raw coincidences ($C_{raw}$) and accidentals ($A_{raw}$) were measured with 0.1 ns timing bins and an integration time of 14 minutes. Coincidence due to dark counts ($D$) were measured separately and subtracted from $C_{raw}$ and $A_{raw}$ to yield $C$ and $A$ (the true coincidence and accidental levels) by fitting the distribution of counts as shown in Fig. 2a. The width of this distribution is dominated by the InGaAs SPAD timing jitter, 0.4 ns. Under continuous wave (CW) pumping with only 180 µW pump power incident into the microring, the coincidence rate was $1.1 \times 10^{-3}$ per detector gate and a pair generation rate (PGR) of 440 kHz. We measured a CAR of $46 \pm 7.6$ (the uncertainties are one standard deviation values). We detuned the laser from the microring resonance by 40 pm; Fig. 2b shows the absence of the coincidence peak above the accidentals, showing clearly that the microring is an efficient generator of photon pairs in this low-power regime.

To show that data streams can be used for pair generation, we re-established resonance, and externally modulated the hybrid laser light into a 10G NRZ (non-return-to-zero) PRBS7 data stream with an extinction ratio of 10 dB. The average pump power was about 5 dB lower compared to the CW case. The distribution of coincidences is shown in Fig. 2c; with the measured CAR of $44 \pm 24$ at a coincidence rate of $5.5 \times 10^{-4}$ per detector gate and PGR of 38 kHz. While there is no hard CAR specification, this measurement does exceed the CAR value of $\sim 10$ that has been used previously in the literature, e.g., [8] explicitly uses this value to numerically estimate a 5% error rate of a Quantum Key Distribution (QKD) system using entangled photon pairs and time correlation measurements. We verified the non-classical correlation between the Stokes (S) and anti-Stokes (aS) generated photon pair by calculating the Cauchy-Schwarz inequality which is satisfied by classical fields [9], \(|g^{(2)}_{S-aS}(0)|^2 \leq g^{(2)}_{S-S}(0) g^{(2)}_{aS-aS}(0)\). The inequality was obeyed in Fig. 2b when the microring was off-resonance; the detectors measured weak residual classical laser transmission, showing no useful pair generation. The inequality was violated by 51 and 7 standard deviations for the CW (Fig. 2a) and pulsed (Fig. 2c) pump cases.

To our knowledge, this is the first report of room-temperature non-classical photon-pair generation using wafer-scale fabricated hybrid silicon lasers and micro-resonators. These results may enable the development of microchip-based integrated quantum optical communications in, and using the available resources of, real data networks.

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