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Generation of squeezed quantum microcombs with silicon nitride integrated photonic circuits

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A two-mode squeezed microresonator-based frequency comb is demonstrated with CMOS-compatible silicon nitride integrated photonic circuits. Seventy quantum modes, in a span of 1.3 THz, are generated in an integrated Kerr microresonator at telecommunication wavelengths.

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Squeezed light [1] has broad applications in science and technology, ranging from quantum-enhanced sensing [2] to demonstrating quantum computational advantages [3]. Recently, there has been increasing interest in photonic continuous-variable-based quantum computing (CVQC) [4], which demands a large number of squeezed quantum modes (qumodes) generated with scalable optical platforms. While scalable generation of squeezing is actively pursued with integrated photonic circuits (IPCs) [5–8], further combination of squeezing and microresonator-based frequency combs (microcombs) introduces an additional dimension for scalability through frequency multiplexing [9].

In this work, we generate a squeezed quantum microcomb [9] with 70 qumodes from CMOS-compatible silicon nitride (SiN) IPCs [Fig. 1(a)]. Our demonstration creates 35 pairs of unconditional Einstein–Podolsky–Rosen (EPR) entanglement between the optical fields in a frequency comb spanning 1.3 THz. The unconditional entanglement is created by the broadband Kerr parametric gain in the microresonator and verified through two-mode squeezing measurements. The number of measured qumodes is limited not by the resonator but by the span of the local oscillators (LOs) used in the balanced homodyne detection. The IPC-based squeezed quantum microcomb is compatible with heterogeneous integration with active and passive IPC components [10], e.g., lasers, modulators, photodiodes (PDs), and interferometers, and thus can serve as scalable building bricks for compact and versatile quantum devices for a wide range of applications.

The microresonator used in this experiment is an integrated, bus-waveguide coupled Si_3N_4 resonator with a cross section of 2.3 µm width × 0.8 µm height. The free spectral range (FSR) of the resonator is 17 GHz. A racetrack shaped resonator with Euler bending is used to minimize the resonator footprint and to reduce avoided mode crossing in the resonator [11,12]. At 1550 nm, the intrinsic (loaded) Q-factor of the resonator is $5.7(0.61) \times 10^6$, yielding an escape efficiency of 89 %.

In the experiment, a 1550 nm continuous-wave (CW) laser amplified by an erbium-doped fiber amplifier (EDFA) is split to pump the resonator and drive the LOs simultaneously [Fig. 2(a)]. The pump power for the resonator is set to 398 mW, which is 1 dB below the resonator's parametric oscillation threshold of 501 mW. All optical powers are measured in the optical fiber before pump light couples into the chip. Lensed fibers are used to couple light into and out of the SiN chip. The output fiber is followed by a fiber-Bragg-grating (FBG) filter, which separates the pump laser and the squeezed microcomb. A pair of lines in an electro-optic modulation (EOM) frequency comb with a comb spacing identical to the microresonator FSR is selected as bichromatic LOs by using a line-by-line waveshaper (WS) [9]. The LO phase is ramped periodically via a phase modulator (PM). The squeezed microcomb and the LOs are combined using a 50/50 coupler and detected on balanced PDs for homodyne measurement. The noise level is recorded using an electrical spectrum analyzer (ESA).

Figure 2(b) shows the quadrature noise variance (blue) relative to the shot noise (red) for qumodes (−10, 10). Raw squeezing of 1.1 dB and anti-squeezing of 6.3 dB is observed. Figure 2(c) presents the quadrature noise variances of 70 qumodes (35 simultaneously squeezed comb pairs) measured within a 1.33 THz optical span. The optical loss limits the raw squeezing to 1.1 dB, which is similar to the first vacuum squeezing demonstrations in SiN resonators [6,7] and slightly lower than the 2.1 dB squeezing attained

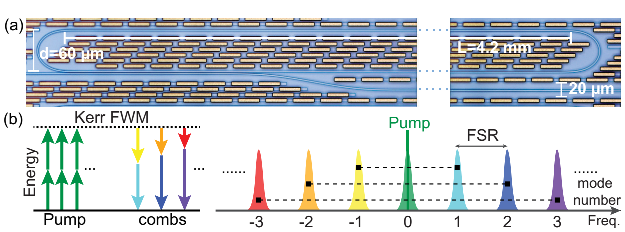

Fig. 1. (a) Microscope picture of an integrated racetrack SiN microresonator. (b) Conceptual illustration of a two-mode squeezed quantum microcomb. The Kerr four-wave mixing (FWM) in the microresonator creates broadband parametric gain and unconditional EPR entanglement of the optical quadrature fields between frequency modes n and $-n$, which are connected by dashed black lines in the optical spectrum.

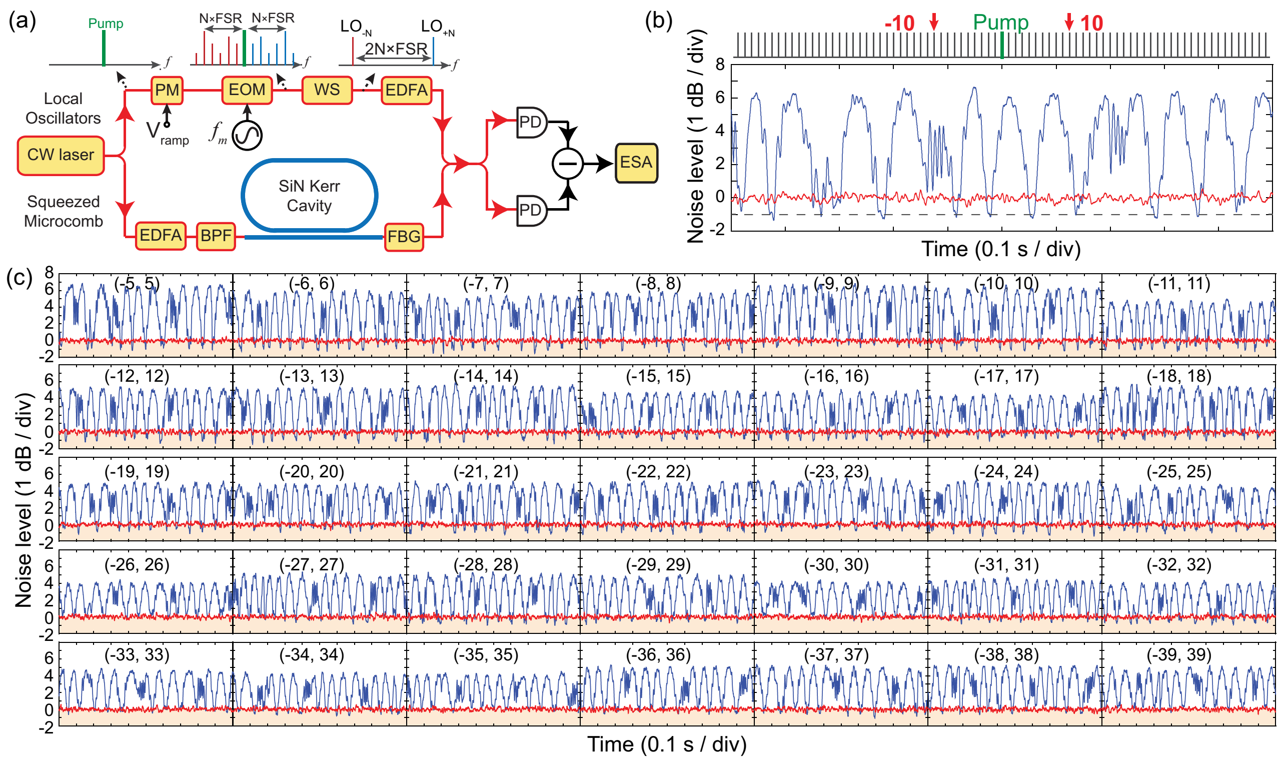

Fig. 2. (a) Simplified experimental setup for squeezed microcomb experiments. (b) Quadrature noise variance (blue) relative to shot noise (red) as a function of time for qumode pair $(-10,\ 10)$. A dashed black line indicates 1 dB below the shot noise level. (c) Quadrature noise variances (blue) relative to shot noise (red) of all 70 qumodes. All measurements are taken at 2 MHz frequency, 100 kHz resolution bandwidth, and 100 Hz video bandwidth.

in a quantum microcomb generated in the taper-fiber-coupled silica resonator on a silicon chip [9,13]. The total efficiency after the resonator is 35%, and is dominated by the chip-to-fiber coupling loss (2.3 dB), off-chip filter loss (2 dB), and 95% PD quantum efficiency. 4.4 dB on-chip squeezing can be inferred after correcting system losses. We noticed that while anti-squeezing levels are very consistent for all comb modes, squeezing vanishes at some specific mode numbers, e.g., mode $(-26,\ 26)$ and mode $(-39,\ 39)$. Interestingly, the squeezing can be revived for all these modes when the frequencies of the bichromatic LOs are detuned slightly, $f_{\mathrm{LO},\pm} = \pm N \times \mathrm{FSR} \pm f_{\mathrm{offset}}$. For example, at an offset frequency equaling three-tenths of the resonance linewidth, the squeezing of modes $(-26,\ 26)$ and $(-39,\ 39)$ revive to 0.3 dB and 0.6 dB, respectively. This phenomenon, where squeezing is maximized at a non-zero offset frequency, occurs in at least 15 out of the 35 mode pairs measured here. Further theoretical and experimental investigations are required in the future to understand this phenomenon.

In summary, we generated a squeezed quantum microcomb with IPCs, which has the potential to be heterogeneously integrated with other integrated photonic components for applications in quantum computing, communications, and sensing.

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Data availability. Data underlying the results in this paper may be obtained from the authors upon reasonable request.

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