A squeezed quantum microcomb on a chip

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The optical microresonator-based frequency comb (microcomb) provides a versatile platform for nonlinear physics studies and has wide applications ranging from metrology to spectroscopy. The deterministic quantum regime is an unexplored aspect of microcombs, in which unconditional entanglements among hundreds of equidistant frequency modes can serve as critical ingredients to scalable universal quantum computing and quantum networking. Here, we demonstrate a deterministic quantum microcomb in a silica microresonator on a silicon chip. 40 continuous-variable quantum modes, in the form of 20 simultaneously two-mode squeezed comb pairs, are observed within 1 THz optical span at telecommunication wavelengths. A maximum raw squeezing of 1.6 dB is attained. A high-resolution spectroscopy measurement is developed to characterize the frequency equidistance of quantum microcombs. Our demonstration offers the possibility to leverage deterministically generated, frequency multiplexed quantum states and integrated photonics to open up new avenues in fields of spectroscopy, quantum metrology, and scalable, continuous-variable-based quantum information processing.

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**Results**

**Squeezed quantum microcombs.** The microresonator used in this work is a 3 mm diameter silica wedge resonator with 22 GHz FSR on a silicon chip. The resonator’s intrinsic quality factor ($Q_i$) is 79 million, and a single-mode tapered fiber is used as the coupling waveguide. The resonator is overcoupled to achieve large field escape efficiency, $\eta = \kappa_s / (\kappa_c + \kappa_o)$, of 83%, where $\kappa_0$ and $\kappa_c$ are the intracavity dissipation rate and the resonator-waveguide coupling rate. An amplified continuous-wave (cw) laser is used as the pump of the resonator, and its frequency ($\omega_p$) is phase-locked to the resonance mode at 1550.5 nm through Pound–Drever–Hall (PDH) locking technique. The pump power in this experiment is set to 120 mW, which is 0.5 dB below the parametric threshold of 135 mW. The dependence of squeezing on the input pump power is discussed in the Methods section. At the through port of the resonator, a narrow-band fiber-Bragg grating (FBG) filter is used to filter out the pump field and the amplified spontaneous emission (ASE) noise from the erbium-doped fiber amplifier (EDFA). In principle, the bichromatic LOs for two-tone homodyne detection can be derived from a soliton microcomb. However, in the present measurement, an electro-optic modulation (EOM) frequency comb is used, where tens of modulation sidebands are created by strong electro-optic phase modulation at modulation frequency $f_{\text{cm}}$ on the cw-laser. A programmable line-by-line waveshaper is then used to select a pair of comb lines as the LOs (see Fig. 2). A periodic ramp voltage is applied on a phase modulator (PM) with $V_{\text{ramp}} = 2.3$ V to scan the phase of the LOs. The LOs and the resonator pump laser are coherent with each other since they are derived from the same cw-laser, and the electro-optic modulators coherently transfer photons from the pump to the modulation sidebands. A detailed description of the experimental setup is provided in the “Methods” section.

The quadrature noise variances of 20 sets of comb pairs (40 qumodes) are measured by means of balanced homodyne detection. To measure the quadrature noise variance of qumodes $\sim N|N\rangle$, the EOM comb modulation frequency $f_{\text{cm}}$ and the programmable waveshaper are adjusted to precisely match the frequencies of LO pairs to $\omega_p \pm N \times D_i$, where $N$ is the relative mode number from the mode being pumped ($N = 0$), and $D_i / 2\pi = 21.95258$ GHz is the FSR of the resonator at 1550.5 nm wavelength. In each measurement, the phase of the LOs is ramped to yield varying quadrature variances. Figure 2b shows a
representative quadrature noise variance (blue) relative to the shot noise (red) for qumodes (−4, 4). A 30-point moving average is used to smooth out the fluctuations in the noise variance measurement. The raw squeezing of 1.6 ± 0.2 dB and anti-squeezing of 5.5 ± 0.1 dB are directly observed, and they are obtained by averaging the displayed extrema. The uncertainty is concluded with a 95% confidence interval under t-distribution. The quadrature noise variances of all 40 qumodes are shown in Fig. 2c, and squeezing/anti-squeezing are observed for all 40 qumodes. The number of measurable qumodes is limited by the 1 THz optical span of the EOM comb. All measurements are taken at 2.7 MHz frequency, 100 kHz resolution bandwidth (RBW), and 100 Hz video bandwidth (VBW) on an electrical spectrum analyzer (ESA). The noise levels of qumodes (−1, 1) to (−3, 3) are not presented here as their measurements are affected by the transmitted ASE noise from the EDFA near the pump frequency. This can be addressed in the future by using a filter with bandwidth much smaller than the FSR of the resonator, or by increasing the intrinsic quality factor of the cavity and reducing the parametric oscillation threshold to eliminate the need for the EDFA. Finally, as shown in Fig. 2d, no quantum correlation (two-mode squeezing) is observed for uncorrelated comb pairs. This serves as a critical check for our two-tone homodyne detection.

The raw squeezing and anti-squeezing levels of all 40 qumodes are summarized in Fig. 3a. The raw squeezing in our experiment is primarily limited by the 83% cavity escape efficiency, 1.7 dB optical loss, and ~89% photodiode quantum efficiency. The total efficiency after the tapered fiber is 60%. Our 1.6 ± 0.2 dB raw squeezing is among the highest raw squeezing measured for a microresonator, which has thousands of longitude resonance modes with their frequencies separated by the resonator free-spectral-range (FSR), as shown in (b). Also shown is the image of a silica microresonator on a silicon chip used in this work. d Conceptual illustration of the two-mode squeezing wavefunctions in position (left) and momentum (right) basis, where (ℏωn − ℏω) and (ℏp + ℏp) have uncertainty level below the vacuum fluctuation (dashed circle). The electrical field of the n-th optical mode is E_n = ℏω_n + ℏp_n sin ℏω_n t, where ℏω_n and ℏp_n are the in-phase and out-of-phase quadrature amplitudes of the mode at frequency ℏω_n.

Squeezed microcomb qumode spectroscopy. A qumode spectroscopy method is developed to characterize the frequency equidistance of squeezed qumodes, a prerequisite of frequency combs. Similar to the classical cavity mode spectrum, we can define the relative qumode spectrum as Δω_n = ω_n - ω_0 - N × D_1, where ω_0 is the optical frequency center of the N-th qumode. The relative qumode spectrum represents the qumode frequency deviation from equidistance. To identify the relative qumode spectrum, the two-sided squeezing/anti-squeezing spectral line shape is measured for each pair of qumodes, and the center frequency of the spectral line shape yields the relative qumode frequency. In the measurement, the +N-th LO frequencies are detuned by ±δ from the equidistant frequencies, +N × FSR, and noise variances are measured at each detuning point for qumodes (−N, N). For each pair of qumodes, the detuning (δ) is varied from −30 MHz to +30 MHz with an interval of 5 MHz, which sets the resolution of the line shape measurement. Measurements of qumodes (−4, 4) at δ = −20, −10, 0, 10, 20 MHz
are shown as examples in Fig. 4b. At each detuning point, squeezing and anti-squeezing levels can be extracted by averaging the extrema. We plot the squeezing/anti-squeezing levels versus detuning ($\delta$) for all qumodes in Fig. 4c, which manifest the two-sided spectral line shape of the qumodes. The squeezing/anti-squeezing extraction below 0.5 dB has relatively poor accuracy, but this does not affect the overall qumode spectrum envelopes. The relative frequencies of the qumodes, i.e., relative qumode spectrum, can be obtained by identifying the centers of the anti-squeezing line shapes via Lorentzian fitting. The average root mean square deviation of the fitting is only 0.15 dB, showing an excellent agreement between fitting and measurements. $\Delta \omega_1^Q$ and $\Delta \omega_2^Q$ of all the qumodes are plotted in Fig. 4d, and their deviations from equidistant are within the 5 MHz spectroscopy resolution limit for the entire 1 THz optical span of the quantum microcomb. The qumode spectrum overlaps well with the two-sided averaged cold cavity mode spectrum, $-(\Delta \omega_N + \Delta \omega_{-N})/2$, which represents the averaged deviation from equidistant of the cold cavity mode $N$ and $-N$. It should be noted that in the qumode spectrum measurement, the cavity is pumped by >100 mW power, which could alter the cavity mode spectrum through thermo-optic effect and self/cross-phase modulation effects. Further study in the future is necessary to understand the requirement for perfectly equidistant frequencies of qumodes. In this measurement, the cavity escape efficiency is adjusted to 77% to achieve a more stable coupling condition as the entire measurement spans over 18 hours. As a result, the amount of squeezing/anti-squeezing at $\delta = 0$ MHz is different from that in the Fig. 2. In this experiment, the escape efficiency is adjusted by varying the relative position between the microresonator and the tapered fiber. The stability of the escape efficiency can be dramatically improved by packaging the microresonator systems or by integrating the coupling waveguide and the resonator on the same chip.

**Discussion**

In summary, we have demonstrated a deterministic two-mode-squeezed quantum microcomb in a silica microresonator on a
The beam from the cw laser is amplified by an EDFA to 200 mW and is phase modulated by three cascaded electro-optic PMs at frequency \(f_m\), which is provided by a signal generator (Keysight, PSG E8257D). The modulators are driven by amplified electrical signals that are synchronized by electrical phase shifters (PSs). The output power of the electrical amplifiers (Amps) is ~33 dBm. As the EOM comb and the microresonator share the same pump laser, the LOs derived from the EOM comb are inherently coherent with the squeezed microcomb. A typical EOM comb spectrum is shown in Fig. 3b (blue line), and the cw pump laser spectrum (black) is also shown as a reference. The EOM comb is then sent to a programmable line-by-line waveshaper (Finisar 1000A, filter bandwidth setting resolution: ±5 GHz), which can control the amplitude and phase of each EOM comb line. To measure the noise variance of qumodes \((-N, N)\), the waveshaper is set to only pass the comb lines whose frequencies are \(\pm \Delta f\) apart from the pump laser, as an example. The LOs for qumodes \((-23, 23)\) are shown in Fig. 3b (red line). Finally, the LOs are amplified to ~17 mW and are combined with the squeezed microcomb for balanced homodyne detection. It should be noted that the relative phase between the local oscillator and the squeezed field could be different from the phase shift applied by the PM in the LO optical path. This is because environmental fluctuations, e.g., ambient temperature, can cause phase variations in fibers in both LO and squeezed light paths. Finally, the electrical amplifiers in the EOM comb output at 18 GHz, which is smaller than the FSR of the resonator (represented by \(f_N\)). As a result, the EOM modulator frequency, \(f_m\), is set to \(n/m \times f_N\) such that the frequency of the \(m\)-th EOM comb line can align with that of the \(n\)-th resonator mode. The modulation frequencies used in the experiment are: \(f_m = 3/4 \times f_N = 16.464438\) GHz for mode pairs \(\pm 6, \pm 9, \pm 12, \pm 15, \pm 18, \pm 21\); \(f_m = 2/3 \times f_N = 14.635056\) GHz for mode pairs \(\pm 8, \pm 14, \pm 16, \pm 20\). For mode pairs of \(\pm 5, \pm 7, \pm 11, \pm 13, \pm 17, \pm 19, \pm 22, \pm 23\), modulation frequencies of \(5/7 \times f_N = 15.688417\) GHz, \(7/9 \times f_N = 17.074423\) GHz, \(11/15 \times f_N = 16.098562\) GHz, \(13/17 \times f_N = 16.787270\) GHz, \(17/23 \times f_N = 16.223823\) GHz, \(19/25 \times f_N = 16.839646\) GHz, \(22/29 \times f_N = 16.653684\) GHz, and \(23/29 \times f_N = 17.410870\) GHz are used, respectively.

The phase noise of the signal generator that drives the EOM comb contributes to the phase fluctuation of the local oscillator, which could potentially affect squeezing measurement. Here, we estimate its impact on our measurement. The root mean square (RMS) of phase jitter from the signal generator can be calculated from its single-sideband phase noise by integrating the phase noise from the electrical spectrum analyzer (ESA) VBW used in the squeezing measurement (100 Hz), to the bandwidth of our balanced photodetection circuit (250 MHz). The RMS of phase jitter \((\Delta \phi)\) is calculated to be 0.0024 rad (0.14°) for comb mode 1 (-22 GHz), and is 0.0535 rad (3.2°) for comb mode 23 (-0.5 THz). After taking account of this phase fluctuation, the observable level of squeezing is

\[
R \approx R_0 \cos \Delta \phi + R_\Delta \sin \Delta \phi,
\]

where \(R_0\) and \(R_\Delta\) are the variance of output squeezing and anti-squeezing, respectively. For the current experimental condition, assuming 2 (7) dB squeezing (anti-squeezing) at mode 4, and 1 (5) dB squeezing (anti-squeezing) at mode 23 after optical losses, the phase fluctuation will cause the measured squeezing \((R)\) to be 0.003 and 0.04 dB lower than the actual squeezing \((R_0)\) at mode 4 and mode 23, respectively. It should be noted that the N-th comb line in the EOM comb has N times the RMS phase jitter of the 1st comb line in the EOM comb. Therefore, when scaling up the number of comb lines in an EOM comb through supercontinuum generation for squeezing measurement, the phase noise of the signal generator should be improved accordingly to maintain the low phase fluctuation of the LOs. A possible way to obtain exceptional phase noise performance for the EOM comb is through electro-optical frequency division, where the signal generator is synchronized to stable optical references.

Characterization of balanced photodiodes. In the two-mode squeezing noise variance measurement, the balanced photodiodes (IDSU, ETX 300T) are operated in the shot-noise-limited regime. The electrical circuit for balancing the photodiodes is home-built, and a common-mode rejection ratio of 31 dB is measured. The shot noise-limited regime is verified by the linear relationship.
between the noise power of the balanced photodiodes and the optical input power, which is shown in Fig. 6a. The measurement is done at 2.7 MHz with 100 kHz RBW. The electrical spectra from the balanced photodiodes at different optical input powers are shown in Fig. 6b. The resonance peaks in the dark noise are likely caused by the electrical circuits in the balanced photodiodes. At 16.6 mW input power, the electrical spectrum is relatively flat. The spectra roll-off is around 20 MHz.

**Dependence of squeezing on optical pump power.** The dependence of squeezing and anti-squeezing on optical pump power is measured for qumode \((-4, 4)\) and is presented in Fig. 6c. Ideally, when there is no optical loss, vacuum squeezing should increase with the pump power until the pump power reaches the OPO threshold. However, as the amount of squeezing in our experiment is primarily limited by optical losses, the increase of squeezing can no longer be observed when the pump power is roughly above half of the OPO threshold. On the other hand, the anti-
squeezing increases with the pump power. This observation is consistent with measurements in previous reports.8,9

Data availability
Source data for Figs. 2–6 can be accessed at https://doi.org/10.6084/m9.figshare.14921670. Additional information is available from the corresponding author upon reasonable request.

Code availability
The codes that support the findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions
X.Y., O.P., Z.Y., and M.J. conceived the idea and designed the experiments. Z.Y. and M.J. performed the measurements. D.J. and H.L. fabricated the microresonator. X.Y., O.P., Z. Y.M.J., and S.S. analyzed the data. All authors participated in preparing the paper and contributed to the discussions. X.Y. supervised the project.

Competing interests
XXX.

Additional information
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