Spectroscopy characterization of quantum modes in an on-chip squeezed microcomb

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Abstract: We characterized the spectrum of 40 quantum modes in an on-chip squeezed microcomb. A theoretical model is developed to explain how cavity dispersion affects the squeezing and the frequency equidistance of these quantum modes.

Multiplexed squeezed states provide a promising path towards scalable universal quantum computing [1–6]. Miniaturization of such quantum resources will be critical for photonic quantum technology. Recently, a squeezed quantum optical frequency comb is generated in a single ultra-high Q microresonator on a photonic chip; in a 1 THz optical span, 40 frequency multiplexed quantum modes are directly observed in the form of 20 sets of two-mode squeezing comb pairs [7]. As shown in Fig. 1 (a), a 3 mm diameter silica wedge resonator with 22 GHz free-spectral-range (FSR) on a silicon chip, is used as an optical parametric oscillator (OPO) in this work. This microresonator leverages Kerr nonlinearity to provide a broadband parametric gain through four-wave mixing (FWM) process among cavity resonance modes. The non-classical correlation in this parametric process creates unconditional Einstein-Podolsky-Rosen (EPR) entanglement, i.e., two-mode squeezing, between the optical quadrature fields of the qumode pairs (Fig. 1 (b)). Understanding the frequency equidistance of the qumodes in this quantum frequency comb platform will be essential for its applications in large-scale continuous-variable-based quantum information processing [8]. In this work, we developed a high-resolution spectroscopy method to experimentally characterize the frequencies of the qumodes and consecutively the qumode spectrum which is defined as the qumode frequency deviation from equidistance. We also explained the role of cavity dispersion on the qumode spectrum through a theoretical analysis.

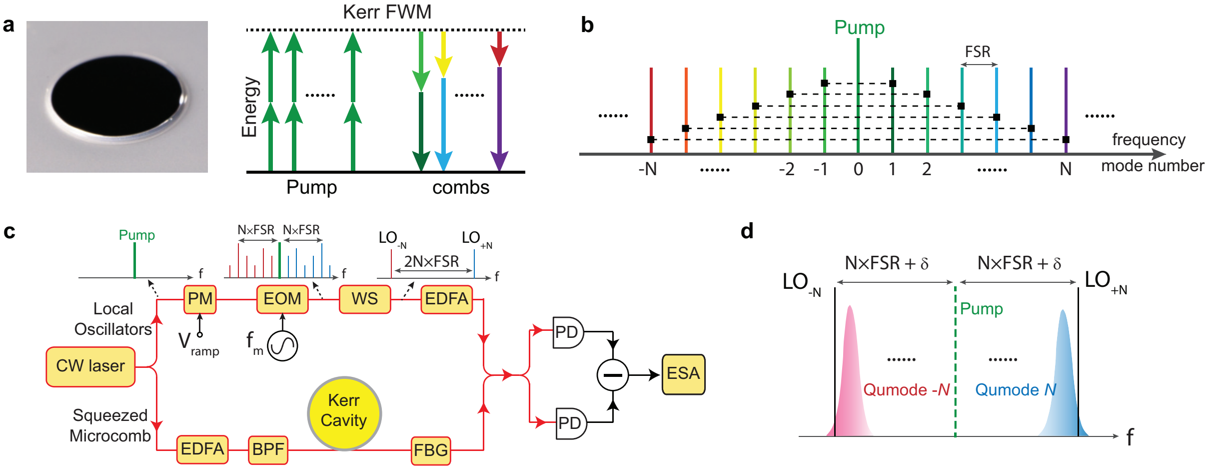

Fig. 1. (a) Silica microresonator on a silicon chip and the illustration of Kerr four-wave-mixing (FWM) process. (b) Optical spectrum in which correlated two-mode squeezing pairs are connected by dashed lines (c) Experimental setup (simplified). (d) Spectroscopy characterization of qumodes (-N,N). The frequencies of the N-th local oscillator pairs can be detuned by δ away from the equidistant frequencies, $\pm N\times$FSR, and the amount of squeezing and anti-squeezing are measured at each detuning point, δ for qumodes (-N,N).

In this experiment, as shown in Fig. 1 (c), a continuous-wave laser simultaneously drives the squeezed microcomb and the local oscillators (LOs). In one optical path, the cw laser is amplified through an erbium-doped

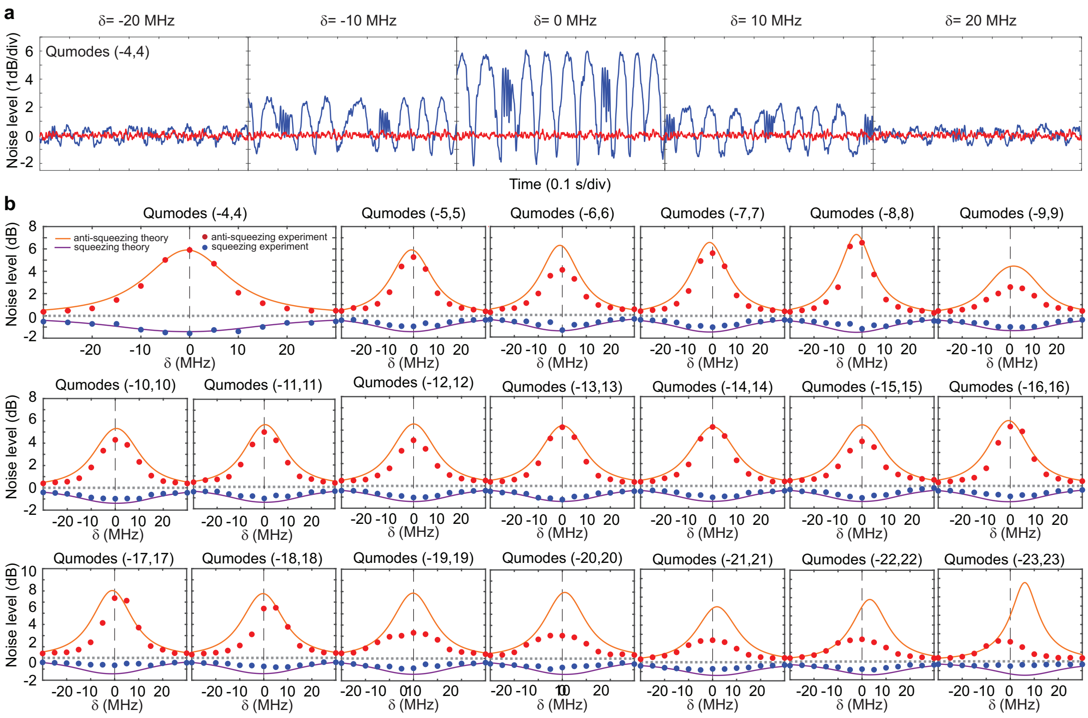

Fig. 2. **(a)** Noise variance measurement of qumodes (-4,4) at LO detuning δ = -20, -10, 0, 10, 20 MHz. The red trace represents shot noise level. **(b)** Squeezing (blue) and anti-squeezing (red) levels extracted from noise variance measurements, as compared to theoretical squeezing (purple line) and anti-squeezing (orange line) levels for all qumodes.

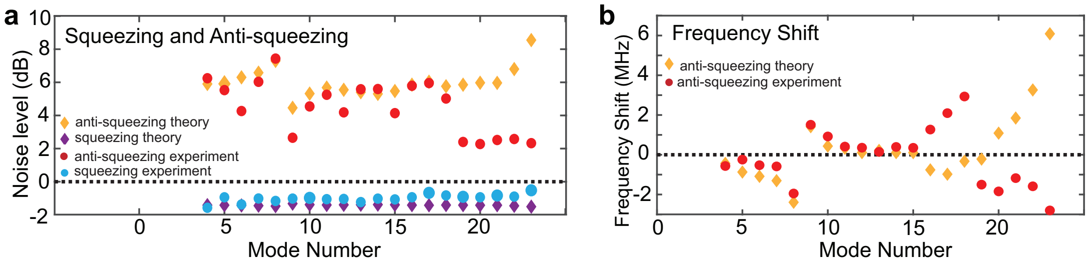

Fig. 3. Comparison of theory and experiment of all qumodes for **(a)** squeezing and anti-squeezing levels, and **(b)** qumode frequency shift, at which maximal anti-squeezing occurs.

fiber amplifier (EDFA) to pump the Kerr cavity and then a fiber-Bragg grating (FBG) filter is used to filter out the pump light and transmit the squeezed light. The LOs are derived from an electro-optic modulation frequency comb (EOM), with a comb spacing (modulation frequency) of f_m. A programmable line-by-line waveshaper is then used to select a pair of comb lines as the local oscillators. A periodic ramp voltage is applied to a phase modulator (PM) to scan the phase of these LOs. The amplified LOs and the squeezed microcomb are combined by a 50/50 coupler and are detected on balanced photo diodes (PDs). The noise level is characterized on an electrical spectrum analyzer (ESA).

The qumode spectrum can be characterized by locating the centers of the anti-squeezing/squeezing spectral line shape for each entangled pair of qumodes. Fig. 1 (d) illustrates the method to measure the relative frequencies for qumodes (-N,N), in which the $\pm N$-th LO frequencies are detuned by $\pm\delta$ from the equidistant frequencies, $\pm N\times$FSR, and noise variances are measured at each detuning point. This measurement for qumodes (-4,4) are shown as examples in Fig. 2 (a) at LO detuning δ = -20, -10, 0, 10, 20 MHz. At each detuning point, squeezing and anti-squeezing levels can be extracted by averaging the extrema. We summarized the squeezing/anti-squeezing levels versus detuning (δ) for all qumodes in Fig. 2 (b). For each pair of qumodes, the detuning (δ) is varied from -30 MHz to +30 MHz with of a 5 MHz resolution. Considering the cavity dispersion (ω_n), we calculated the quadrature variances of electric fields in the frequency domain using nonlinear coupled mode equations [9], in the form of a Taylor expansion series. This analysis shows that a relatively large even-order dispersion in ω_n, results in achieving lower levels of squeezing and anti-squeezing. On the other hand, the odd-order dispersion is responsible for deviating the qumode frequency center from the equidistant frequency. We calculated squeezing spectrum including the measured value for ω_n and to improve the fit, the pump power is adjusted from the actual 89% used in the experiment to 85%. Similarly, the loss incurred after the resonator is increased from 0.4 to 0.6. Comparing the theoretical predictions and measurement results in Fig 2 and 3, proves that our analytical model is accurate among the lower qumodes but becomes less effective at predicting behavior in the higher qumodes. This may come from the fact that our model only accounts for the dispersion, but not the photon redistribution aspect of avoided mode-crossing, which could be more prevalent in higher qumodes.

In conclusion, we characterized the equidistance of 40 qumodes in a squeezed quantum microcomb and developed an analytical description to describe the effect of cavity dispersion on the qumode spectrum and squeezing level. This spectroscopic characterization offers the possibility to design more robust deterministically generated, frequency multiplexed quantum states using integrated photonics which will open up new avenues in fields of spectroscopy [10], quantum metrology [11], and scalable quantum information processing [12].

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