On-Chip Optical Squeezing

Avik Dutt¹, Kevin Luke¹, Sasikanth Manipatruni², Alexander L. Gaeta³,⁵, Paulo Nussenzveig¹,⁴, Michal Lipson¹,⁵

¹School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853, USA
²Exploratory Integrated Circuits, Intel Components Research, Intel Corp, Hillsboro, OR 97124, USA
³School of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853, USA
⁴Instituto de Física, Universidade de São Paulo, P.O. Box 66318, 05315-970 São Paulo, Brazil
⁵Kavli Institute at Cornell for Nanoscale Science, Cornell University, Ithaca, NY 14853, USA
A squeezed light source, i.e. a source with ultra low noise level, below the standard quantum limit (SQL), can enable quantum enhanced sensing, spectroscopy, metrology and quantum information processing. To date, such a non classical light source on-chip, scalable, compact and robust has not been demonstrated. Such a source could not only enable ultrasensitive measurements on chip, but also provide squeezing over high bandwidths in contrast to most sources which usually rely on large optical cavities with narrow bandwidths. Here, we report the observation of squeezed light in an on-chip monolithically integrated platform, generated in a micron-size silicon nitride oscillator with GHz cavity linewidth. We show 1.7dB noise squeezing, i.e. reduction of the noise level below the standard quantum limit, of the intensity difference between two beams generated by an on-chip optical parametric oscillator.

The noise of a light source can in principle be lowered below a level determined by quantum mechanical fluctuations (standard quantum limit, SQL), by using a squeezing process that reduces the noise in the intensity (phase) at the expense of increasing phase (intensity) noise. Such a squeezing process requires an optical nonlinearity and has been demonstrated in several off-chip platforms including optical parametric oscillators (OPOs) using parametric down conversion, and in atomic vapours and optical fibres using four-wave mixing (FWM). In such nonlinear parametric processes two “twin” beams are generated, called signal and idler beams, with strong quantum correlations in the intensity and anticorrelations in the phase noise, leading to noise reduction in the intensity difference between the two beams.
Traditionally squeezed light sources suffer from a fundamental trade-off between low bandwidth and high squeezing. This is because high squeezing factors are usually obtained near the parametric oscillation threshold for OPOs, naturally requiring resonant enhancement of the pump and the oscillating modes. For example lithium niobate\(^\text{10,11}\) and potassium titanyl phosphate (KTP)\(^\text{12,13}\) waveguides have been used as nonlinear gain media to produce squeezed vacuum states, but the absence of a cavity in these structures limits them to low squeezing factors. To date the demonstrated platforms based on free space optical cavities have been shown to generate significant squeezing over only narrow bandwidths of the order of a few tens of MHz corresponding to the sharp cavity bandwidths. Twin beam intensity difference squeezing has been recently demonstrated in whispering gallery mode crystalline resonators made of lithium niobate\(^\text{14}\), but the platform is not integrated on chip, and has a cavity bandwidth of 30 MHz. Recently, Ast et al.\(^\text{15}\) observed a squeezing factor of 1 dB at an analysis frequency of 1 GHz by using a low finesse cavity for field enhancement. However, as Ast et al. point out\(^\text{15,16}\), the consequences are a very high parametric oscillation threshold (65 W intracavity, compared to 7 W intracavity for our resonator).

Here we generate nonclassical squeezed light based on an on-chip OPO in a cavity with a bandwidth of 1 GHz. Owing to the small size of on-chip cavities, it is possible to obtain a large finesse and still have relatively wide cavity bandwidths. Large intra-cavity pump enhancement and strong squeezing can thus be obtained. These OPOs based on FWM, consist of micro-ring resonators fabricated on deposited films of Si\(_3\)N\(_4\) (Fig. 1(a) and inset of Fig. 2). Silicon nitride is chosen as the material because of its high nonlinear refractive index\(^6\) \((n_2 = 2.5 \times 10^{-15} \text{ cm}^2 \text{ W}^{-1}, \text{about } 10\text{ times that of silica})\) and very low
propagation loss (< 0.5 dB per cm). It should be noted that the nonlinear refractive index of silicon is an order of magnitude higher than that of Si$_3$N$_4$, but nonlinear losses such as two photon absorption and free carrier absorption at 1550 nm preclude parametric oscillation in silicon. The devices are compact, with a bus waveguide length of 1.5 mm and a ring circumference of 1.8 mm, corresponding to a free spectral range (FSR) of 80 GHz. Note that the OPO can generate in principle a very large number of beams spanning almost an octave$^{17,18}$. Here we generate squeezing by using a pump power that is just above the threshold, when only two modes oscillate.

In order to obtain significant squeezing, the cavity output coupling losses must be a large fraction of the overall losses. Relatively large losses are also desired for a large cavity bandwidth. On the other hand, a low pump power threshold is desirable, since it avoids detrimental thermal effects and also minimizes the influence of technical noise from the pump laser. The squeezing factor depends on the ratio between the internal ring losses, given by the ring's intrinsic quality factor ($Q_i$), and the coupling coefficient between the bus waveguide and the ring resonator, determined by the loaded quality factor ($Q_L$). The smaller this ratio, the better squeezing is obtained. The simultaneous requirement of large losses and low threshold is a challenge, since the threshold is inversely proportional to the product of $Q_i$ and $Q_L$. We can meet the requirements by designing a ring with a very large $Q_i$, larger than 2 million, and operating in the highly overcoupled regime. The high intrinsic $Q$, achieved using the recently demonstrated fabrication process of thick Si$_3$N$_4$ deposition$^{19}$, enables the generation of the beams with ultra-low pump power despite operating in this overcoupled regime. The loaded $Q$ (200,000) is designed to be much lower than the intrinsic $Q$ ($Q_i \approx 2$ million), facilitating a broad cavity linewidth of the order of 1 GHz.
The key to the realization of on-chip optical squeezing is the engineering of the dispersion and quality factors of the longitudinal modes of the microring resonator, to generate the twin beams at two well distinguished frequencies with low threshold pump powers. In contrast to many table top squeezing experiments, where the twin beams can usually be separated spatially based on their different polarizations, in on-chip platforms the beams are co-propagating in the same output waveguide with equal polarizations, and therefore in order to be distinguishable, the beams are required to have well separated frequencies. A delicate interplay between the group velocity dispersion and the quality factor of the ring, which together shape the FWM gain curve around the pump determines at which frequencies the twin beams will be generated. Here we engineer the structure to ensure that the idler and the signal beams are generated at two well distinguished wavelengths separated by over 10 nm, at 1540.2 and 1559.2 nm when the OPO is pumped at 1549.6 nm, enabling the beams to be spatially separated using traditional grating filters with very low loss. These two modes are 15 cavity resonances away from the pump wavelength, as can be seen from the transmission spectrum of the ring shown in Fig. 1(b). The large wavelength separation between twin beams not only enables spatial separation of the twin beams, but it also enables filtering of the pump wavelength, which is essential to prevent the residual pump from affecting the twin beam squeezing measurements.

We measure the squeezing in intensity difference of the two beams generated when the OPO is pumped above threshold by comparing the noise level to the shot noise level generated from the coherent pump source. The experimental setup used to measure the squeezing is shown in Fig. 2. The rings were pumped by a continuous wave, tunable laser at 1549.6 nm followed by an erbium doped fibre amplifier (EDFA) and a bandpass filter (BPF)
to reduce the amplified spontaneous emission noise generated by the EDFA. The output from the waveguide was collected with a high NA (NA = 0.25) objective lens, leading to loss of less than 1.5 dB. A diffraction grating with an efficiency of 85% was used to spatially separate the pump and the two beams. After blocking the pump, the beams were focused on the two inputs of a Thorlabs PDB150C balanced detector. The balanced detection system consists of a pair of well-matched InGaAs photodiodes with a quantum efficiency of 96%, followed by a low noise transimpedance amplifier to amplify the difference in photocurrents between the detectors. We calibrate the shot noise level at different optical powers by splitting the pump beam at a 50:50 beam splitter and focusing the two halves of the beam on the two detectors. The shot noise level is linearly proportional to the optical power in each beam, in accordance with theory. A linear dependence confirms that the common-mode rejection ratio of our differential amplifier is large enough to get rid of technical noise in the system using balanced detection, and that the detectors are not saturated.

We observe 1.7 dB of sub-shot noise intensity correlation between the twin beams. Twin beam intensity difference measurements are presented in Fig. 3. The black line corresponding to the electronic noise floor of the detection system represents the dark noise of the detector and the electronic noise of the amplifier, measured with inputs to both the photodiodes blocked. The red line corresponds to the twin beam intensity correlation measurement, which is below the shot noise level, demonstrating clear intensity difference squeezing. These measurements were taken at Fourier analysis frequencies from 0.5 to 5 MHz, using a spectrum analyser with a resolution bandwidth of 30 kHz and a video bandwidth of 100 Hz. Squeezing is not observed at very low frequencies, owing to technical
noise in the pump laser. The on-chip OPOs used here could in principle act as platform for generating large squeezing factors over broad bandwidths due to the highly overcoupled design of the rings. The observed noise reduction of 1.7 dB is less than that expected from the ratio of $Q_i$ and $Q_L$, even taking into account detection losses. This is due to residual pump noise and the possible rotation of the optimally squeezed quadratures by the process of FWM$^{21,22}$. It should thus be possible to reach much stronger noise reductions in this platform. Fundamentally the on-chip OPOs are expected to exhibit squeezing over GHz bandwidths in view of the broad linewidth of the cavity. We have demonstrated here squeezing in the MHz range, limited only by the bandwidth of our detectors.

These results represent the first experimental observation of optical squeezing in an integrated CMOS compatible platform. This demonstration paves the way for a myriad of on-chip quantum optics experiments over broad bandwidths in a scalable, compact and robust platform. For instance, one can envision the introduction of non-classical light sources into future data communications by leveraging the mature infrastructure of microelectronics, currently being introduced into silicon photonics$^{23}$.

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**Author contributions**

A. D. conducted the experiments and carried out the data analysis. K. L. fabricated the chips. S. M. did initial work on the experiments. P. N, M. L. and A. L. G. supervised the project. All authors contributed to writing the paper and discussing the results and implications.

**Competing financial interests**

The authors declare that they have no competing financial interests.

**References**


**Methods**

**Device Fabrication**
The waveguides and ring resonators were fabricated in 800 nm-thick silicon nitride films to provide low loss and high optical confinement. A 4 µm thick silicon dioxide layer was first thermally grown on a virgin silicon wafer as an under cladding. The nitride layer is grown using low pressure chemical vapour deposition (LPCVD) in two steps of 400 nm each, followed by annealing in a nitrogen atmosphere for 3 hours at 1200 °C. The devices are patterned with electron beam lithography using MaN-2403 resist. After exposure and development, the resist was post-exposure baked for 5 min. at 115 °C, and etched in an inductively coupled plasma reactive ion etcher (ICP RIE) using CHF$_3$/O$_2$ chemistry. The devices are finally clad with 250 nm of high temperature oxide (HTO) deposited at 800 °C, followed by 2 µm of silicon dioxide using plasma enhanced chemical vapour deposition.

**Experimental techniques:**

To observe the variance of the intensity difference noise between the two balanced detectors, the RF output of the Thorlabs PDB 150C was sent to an electronic spectrum analyser. A small fraction (5%) of the light coming out of the chip was sent to an optical spectrum analyser (OSA) to observe the onset of parametric oscillation. The setup includes a variable optical attenuator before the grating to calibrate the shot noise level and to check the degradation of squeezing with attenuation of the twin beams.

The intrinsic quality factor, $Q_i$ of the devices was measured from the transmission spectrum of a near-critically-coupled microring resonator on the same chip, which had a larger coupling gap between the ring and the waveguide compared to the microring used for the squeezing measurements. The intrinsic quality factor of the device operating close to critical coupling can be calculated from the following formula$^{24}$:
\[ Q_t = \frac{2Q_{\text{loaded}}}{1 \pm \sqrt{T_{\text{min}}}} \]

where the positive and negative signs in the denominator correspond to under- and over-coupled condition, \( Q_{\text{loaded}} \) is the measured quality factor, and \( T_{\text{min}} \) is the minimum normalized transmission on resonance.
Figure 1: (a) Schematic of the generation of intensity correlated signal and idler beams via four wave mixing in the on-chip microring optical parametric oscillator (OPO). (b) Top: Optical spectrum analyser scan of the light coupled out of the chip, at a pump power just above the parametric oscillation threshold. The Si$_3$N$_4$ ring is pumped at 1549.6 nm, generating signal and idler modes at 1540.2 nm and 1559.2 nm, respectively, which are 15 cavity modes away from the pump wavelength on either side, as can be seen in the bottom figure. The resolution of the scan was 0.1 nm. Bottom: Transmission spectrum of the ring for transverse electric (TE) polarisation.
Figure 2: Experimental setup. EDFA: Erbium doped fibre amplifier. BPF: Bandpass filter. OSA: Optical spectrum analyser.
Figure 3: Intensity difference squeezing between signal and idler beams using a 30 kHz RBW and 100 Hz VBW. 1.7 dB of sub-shot noise quantum correlations are seen between the signal and idler beams around a frequency of 3 MHz. The squeezing extends from an analysis frequency of 2 to 5 MHz.