

# Nanophotonic source of quadrature squeezing via self phase modulation

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Squeezed light are optical beams with variance below the Shot Noise Level. They are a key resource for quantum technologies based on photons, they can be used to achieve better precision measurements, improve security in quantum key distribution channels and as a fundamental resource for quantum computation. Here we demonstrate an integrated source of squeezing based on four wave mixing that requires a single laser pump, measuring 0.45 dB of broadband quadrature squeezing at high frequencies. We identify and verify that the current results are limited by excess noise produced in the chip, and propose ways to reduce it. Calculations suggest that an improvement in the optical properties of the chip achievable with existing technology can develop scalable quantum technologies based on light.

## I. INTRODUCTION

Squeezed states of light are a fundamental building block of quantum optics, as they are capable of generating entangled states in the continuous variable (CV) regime<sup>1</sup>. For this reason, they are the basis to demonstrate fundamental physics principles and develop quantum technologies. For example, squeezed light has been used to generate entanglement<sup>2</sup>, as a resource required for quantum teleportation<sup>3</sup>, and to produce Schrodinger cat states<sup>4</sup>. In quantum key distribution, squeezed states can be employed to enhance security<sup>5</sup> with high compatibility with conventional optical communication technology. In sensing, squeezing has been demonstrated as the optimal resource to use in interferometers to achieve sub-Shot Noise Level (SNL) measurements<sup>6</sup>, and its use for gravitational wave detection has demonstrated outstanding broadband sensitivity<sup>7</sup>. Finally, the hybridization of CV with single photons has been recently proposed to achieve high fidelity logical operations<sup>8,9</sup> for the development of quantum computers able to operate with error correction protocols<sup>10</sup>. The use of squeezing, rather than single photons, allows for the unconditional generation of entanglement<sup>3</sup>, allowing deterministic schemes to achieve quantum advantages over the classical approach.

Efforts have been focused on the development of integrated circuits for CV photonics, including entangled circuits<sup>11</sup>, and homodyne detectors for quantum states<sup>12</sup>. Numerous demonstrations of on chip generation based on spontaneous parametric down-conversion have been achieved in periodically poled Lithium Niobate (PPLN) waveguides at telecommunication wavelength<sup>13</sup>. Even though recent results of on chip generation and manipulation of squeezed states of  $\sim 2$  dB are remarkable,<sup>14,15</sup> the diffusion fabrication process results in low modal confinement, long interaction lengths and high bending losses which strongly limit the potential application for complex on-chip experiments and prevent the direct integration of either photodetectors or superconductive single photon detectors (SSPD). Silicon nitride (SiN) is a promising material for quantum optics application thanks to the wide transparency spectrum and absence of two-photon absorption up to visible wavelengths. SiN photonics has demonstrated

the generate single photons<sup>16,17</sup>, complex optical circuits<sup>18</sup> and SSPD scalable to high photon numbers<sup>19</sup>. Recently, highly enhanced light-matter interactions in silicon nitride (SiN) resonators based on four wave mixing has been used for efficient creation of twin beam squeezed states<sup>20,21</sup> and degenerate squeezed beams based on complex pumping and optical circuit structure<sup>22,23</sup> achieving the level of measured squeezing around 1.5 dB.

Here, we use a single ring resonator and single pump by taking advantage of self phase modulation and generate squeezed states by Kerr effect as proposed by Hoff et al.<sup>24</sup>. Contrary to the original theoretical scheme, we produce two counter propagating bright squeezed states that re-interfere in an integrated Sagnac interferometer to generate a single quadrature squeezed state<sup>25</sup>. This technique has been widely investigated in experiments based on optical fibers<sup>26</sup>, as a way to reject spurious noise and reduce the optical power to avoid detector saturation. We measure 0.45 dB and infer 1 dB of broadband quadrature squeezing at telecommunication wavelengths using an on chip SiN microring structure that was fabricated with CMOS compatible material.

## II. RESULTS

### A. Experimental setup

The optical device was designed to maximize the third order non-linearity in the ring resonators (see Supplemental Material). The photonic device was fabricated from a plain silicon wafer on which  $2\mu\text{m}$  of low loss thermal  $\text{SiO}_2$  is grown by wet oxidation. Then we deposit 500nm plasma enhanced chemical vapour deposition (PECVD) SiN with a 5:2 ratio of  $\text{NH}_3:\text{SiH}_4$ <sup>17</sup>, showing a refractive index of 1.96 at 1550nm. Samples are diced and spun with 450nm of positive resist CSAR. Next, the photonic circuits are exposed with an electron beam lithography system JEOL JBX9300FS, developed and etched with an ICP RIE in fluorine chemistry. The remaining resist is removed and the sample is annealed in  $\text{N}_2$  for 3 hours at 1200 degrees to further decrease the material losses around 1550nm. Finally,  $1.2\mu\text{m}$  of  $\text{SiO}_2$  is deposited as top cladding by using PECVD liquid tetraethoxysilane (TEOS). The SiN photonic circuit consisting of a 2x2 multi-mode interference (MMI) coupler with the output ports connected in a loop to form an integrated Sagnac interferometer. Inside of

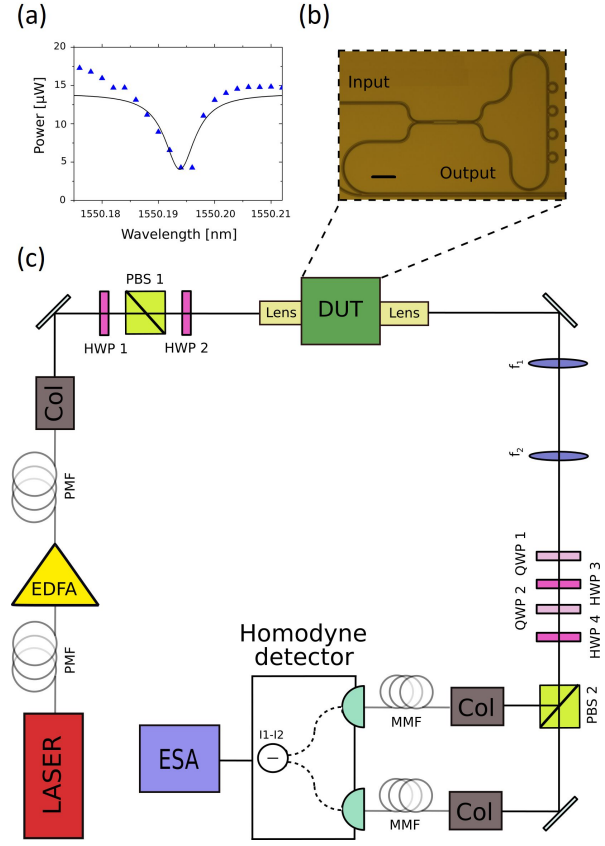
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this loop, four microring resonators were designed with different resonant frequency in the highly overcoupled regime (with different escape efficiency  $> 70\%$ ). This is achieved thanks to a short single mode section that pushes the optical field out of the waveguide in order to achieve high coupling ideality<sup>27</sup>. An optical image of the photonic chip is reported in Fig. 1(b). The device was characterized by performing transmission measurements with a tunable laser. Fig. 1(a) displays the transmission spectrum of the overcoupled ring resonator with escape efficiency 77% used for the experiment. The ring has 30  $\mu\text{m}$  radius and a loaded Q-factor of 238,000, from which propagation losses of 0.32 dB/cm can be extracted.

Fig.1(c) shows a schematic of the experimental setup for generation of the squeezed state (see Supplemental Material). An input beam in diagonal polarization was coupled to the photonic chip via high numerical aperture aspheric lens. In the chip, the horizontal polarization is equally split in the 50/50 MMI and coupled to the ring resonator producing two counter-propagating bright squeezed states thanks to the self phase modulation based on the third-order nonlinear Kerr effect<sup>26</sup>. The beams re-interfere on the MMI and produce an attenuated quadrature squeezed state at the output port, while the majority of the pump is rejected in the input port. At the same time, vertical polarization is unequally split by the MMI (59/41 ratio); the beams counter-propagate back towards the beam splitter where they partially interfere with lower visibility, so that a mW-level beam of light co-propagates alongside the quadrature squeezed state and can be used as local oscillator. This configuration is chosen to simplify the control of the experiment, since there is high phase stability between the local oscillator and squeezed state beams as they share the same optical path. Both beams were out-coupled via an additional lens. Using four waveplates we were able to measure the noise power at different quadratures with a polarization homodyne detection scheme (see Supplemental Material).

## B. Squeezing measurement

The noise spectrum of the light collected from the chip is presented in Fig. 2(a) for three different input powers in the input waveguide (26mW, 39mW and 52mW), while panel (b) presents the spectrum normalized to the shot noise. Squeezing is observed spanning a frequency range of 300 MHz, with a maximum reduction of noise of 0.45 dB. The inferred level of squeezing corrected for the measurement efficiency is estimated to be 1 dB. The squeezing level above  $\Omega \sim 800$  MHz decreases due to the response of the detector and the spectral properties of the ring resonator. This bandwidth is comparable to the one observed in down conversion parametric oscillators by monolithic cavities, but an order of magnitude greater than bow tie configurations, offering high data rate for quantum communication and cryptography while requiring modest power requirements. No squeezing is observed at low frequencies, as excess noise above the SNL is present up to  $\Omega \sim 500$  MHz. We assign the origin of this noise to the thermorefractive effect: statistical variations in the temperature of the chip drive refractive index fluctuations through



**FIG. 1. Experimental setup and optical characterization.** (a) Transmission spectrum of the SiN chip, showing the overcoupled resonance with loaded Q-factor of 238,000 used for squeezing generation. (c) Optical image of the photonic chip, scale bar is 200  $\mu\text{m}$ . The waveguide adjacent to the MMI output is used to facilitate coupling into the chip. (d) Schematic setup for on chip generation of broadband quadrature squeezed states. PMF: polarization maintaining fibre, EDFA: erbium doped fibre, COL: collimator amplifier, HWP: half waveplate, QWP: quarter waveplate, PBS: polarizing beam splitter. DUT: device under test, MMF: Multi mode fibre, ESA: electronic spectrum analyser

the thermo-optic coefficient of the material, introducing phase noise in the propagating beam. The slow diffusion of these random temperature fluctuations results in a noise that decays with the square of the frequency<sup>28</sup>  $\Omega^{-2}$ . In the Supplemental Material we investigate the characteristics of the excess noise to experimentally confirm its thermorefractive origin and provide power, frequency and temperature dependent measurements that corroborate our model.

We further analyze the prospects to suppress this effect and to achieve high level of squeezing. The unwanted noise depends on both the thermo-optic coefficient and the thermal fluctuations induced by the local environment of the ring. Since for many future experiments the generation of non-Gaussian quantum states<sup>1</sup> will require the integration of SSPDs operating at cryogenic temperature, it is expected that the production of the unwanted noise will decrease. Assuming that the ring resonator temperature is lowered to  $< 3\text{K}$ ,

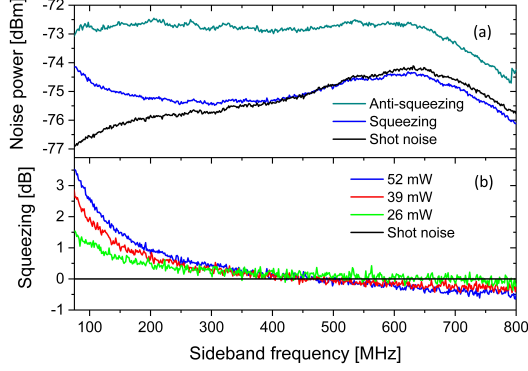


FIG. 2. **Measurements of the squeezing level.** a) Noise spectrum for measured squeezing, anti-squeezing and shot noise for an on-chip pump power of 52mW. The video (VBW) and radio (RBW) bandwidths are set up at 100 kHz and 20 Hz, respectively. Each line is an average of five measurements where each measurement has a sweep time of 10s. b) Squeezing spectrum, for three different input powers before the 50/50 beam splitter, that has been corrected for the noise of the detector and normalized to the shot noise level.

we expect a reduction of this noise by 50 dB, since the thermorefractive effect scales as  $T^2$  and the thermo-optic coefficient of SiN decreases at low temperatures. In such case, we would predict a measurable squeezing level of 1.4 dB at low frequencies under the same pumping conditions. This is limited by the tradeoff between pump power, escape efficiency and noise at room temperature in the current device. An alternative way to reduce the noise that does not require cryogenic operation relies on a more precise control of the photonic interferometer. It has been proposed that the Sagnac works as a purifier of quantum correlations from classically correlated noisy effects such as Brillouin and Raman scattering<sup>25</sup> or even technical noise of the laser<sup>29</sup>. Therefore improving the contrast of our Sagnac interferometer from 23 dB to 60 dB using an interferometer<sup>30</sup> could greatly reduce any classically correlated noise (see Supplemental Material for the effect of the Sagnac interferometer).

In order to understand the dynamics of generated quantum correlated states we use the theory developed by Hoff<sup>24</sup> for the Kerr effect in SiN microring resonators. We verify this model in Fig. 3 by comparing the measured quadrature spectra with theoretical calculations. The assumption describes reasonably well the measured squeezing at high frequencies. This can be supported by the fact that the  $\Omega^{-2}$  scaling of the thermorefractive noise makes it negligible at higher frequencies, so that the noise begins to be dominated by the Kerr squeezing.

### C. Prediction of achievable squeezing level

Finally, we evaluate the possible on chip generation of quadrature squeezed state with already fabricated waveguide using commercially available low pressure chemical vapour deposition, ultra low loss, SiN<sup>31</sup> and the highest-Q SiN ring

resonators<sup>32</sup> with an intrinsic Q factor of 13 and 37 million, respectively. In Fig.4 we calculate the amount of on-chip squeezing considering a ring escape efficiency of 95%. We use the waveguide and ring parameters reported in the respective demonstrations, and assume that the increase coupling does not degrade the intrinsic Q factor. In both cases the amount of squeezing converges to 13 dB, mainly limited by the escape efficiency. More interestingly, for the higher Q factor the power required to achieve such a squeezing level is only 40mW. Provided that there are no additional noise sources that limit the squeezing level, such results could introduce a wide variety of future applications for continuous variable encoding for quantum computing, as 10 dB is considered to be sufficient to achieve fault tolerant universal quantum computation<sup>10</sup>.

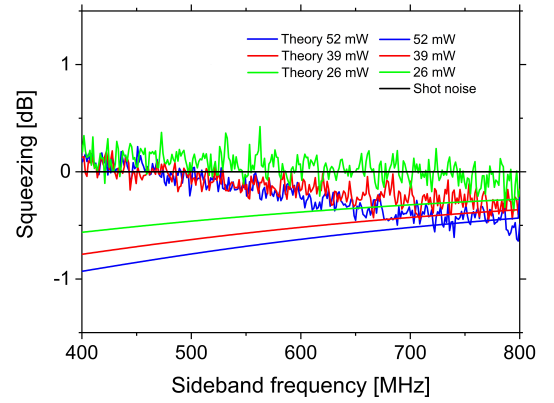


FIG. 3. **Theoretical and experimental squeezing.** Comparison between measured squeezed spectrum and theoretical prediction without thermorefractive noise where the calculations include the overall out-coupling losses.

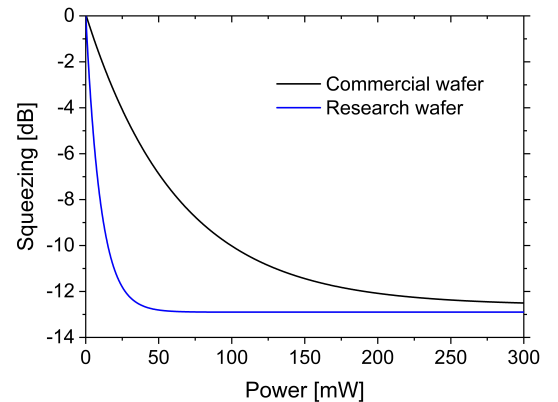


FIG. 4. **Prediction of squeezing with current technology.** Theoretically predicted levels of quadrature squeezing for commercially deposited SiN from<sup>31</sup> and research grade SiN from<sup>32</sup>. The prediction is based on the waveguide and ring dimensions reported in the respective reference, and assuming an escape efficiency of 95%.

### III. DISCUSSION

In conclusion we have studied the generation of broadband quadrature squeezing via self phase modulation, from a CMOS-compatible SiN microring resonator in an integrated Sagnac interferometer, measured in low CW pump regime. Contrary to the alternative PPLN sources which are several mm long and fabricated via proton beam lithography, our process takes full advantage of the standard commercial nanofabrication techniques providing a truly scalable process that can provide hundreds of optical components. We provide demonstrations that the amount of squeezing is limited by the thermorefractive noise that is in principle present in all experiments based on self phase modulation. This noise can be heavily reduced by suppressing the temperature fluctuations operating at cryogenic temperatures and by improving the optical circuit. This would increase the measured amount of squeezing of the current sample under the same pumping conditions and provide sub-SNL light at low frequencies. The use of ultra low loss SiN would result in much higher amount of squeezing for even lower pumping powers. Furthermore, on chip entanglement can be achieved using only two ring resonators and simple integrated optic circuits<sup>11</sup> providing a basis for such fundamental capabilities as quantum teleportation, cryptography and sensing. Finally, using time encoded sources of quadrature squeezed states of light, photon resolving SSPDs, delay lines and integrated germanium photodetectors, could have the potential to achieve fully integrated fault tolerant universal quantum computer<sup>33</sup> and remove the limitation of out-coupling losses. The integration of all components in a single chip would make the experiment phase-stable without the need of additional locking electronics or polarization encoding. This will simplify both the design of the photonic device and the operation of the experiment, while removing the need for many of the elements currently required in CV experiments. These prospects make SiN resonators excellent candidates to expand the applications of integrated sources of squeezed states of light for a broad range of future photonic quantum technology applications and go beyond the limits imposed by bulk optics.

### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### SUPPLEMENTARY MATERIAL

See supplementary material for details of the chip, polarization homodyne detection, noise characterisation and simulations of the Sagnac noise rejection.

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