Gaussian state tomography with self-homodyne analysis cavities of a bright two-mode squeezed state from a nanophotonic chip

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Squeezed states of light are a key resource in quantum information, offering noise levels below the standard quantum limit and enabling applications in quantum communication, computation, and precision sensing. Optical parametric oscillators, in their nondegenerate configuration, are a workhorse source of two-mode squeezing that intrinsically produces continuous-variable EPR entanglement between the twin beams. To observe these EPR-type correlations using the DGCZ entanglement witness, both amplitude-difference and phase-sum quadrature squeezing need to be characterized. However, among these, only amplitude-difference quadrature is directly detectable with balanced photodiodes.

Phase-sum squeezing, and the observation of bright entanglement in nanophotonic systems, was however lacking due to several challenges. Phase squeezing measurements require coherent detection techniques such as homodyne mixing with a local oscillator that is matched in frequency. For two-mode squeezed states, two phase-correlated fields at the signal and idler frequencies are needed. While electro-optic (EO) combs are a common solution for generating such phase-correlated fields, this technique constrains the signal-idler separation to be less than the EO comb bandwidth [1]. Thus, it is important to explore other coherent detection techniques that can access all quadrature combinations of two-mode and multimode quantum fields without being encumbered by narrow comb bandwidths. Recently, we demonstrated seeded optical parametric amplification (OPA) as a promising alternative to above-threshold OPOs, offering improved stability while reaching high level of amplitude-difference squeezing ($\sim$ 5.6 dB) below the OPO threshold [2].

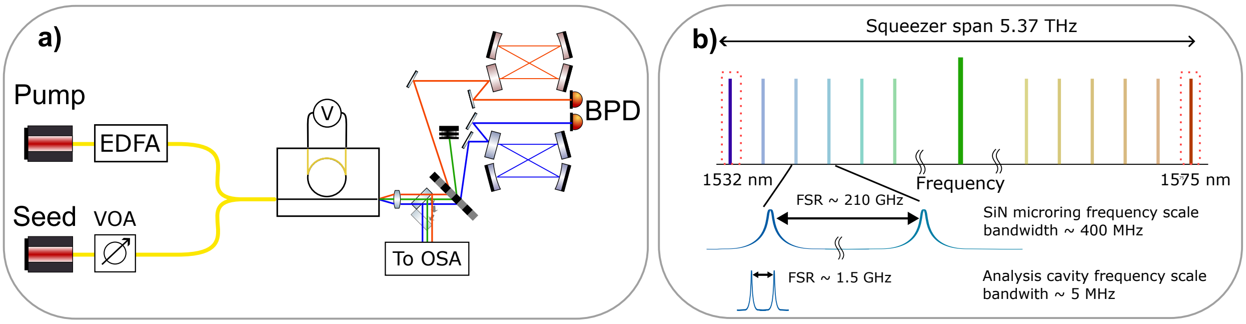

Figure 1: a): Experimental setup. The OPA is generated by a silicon nitride microring resonator, pumped by a strong $\sim$ 150 mW laser and a weak $\sim$ 10 μW seed. b. Frequency scale of the different elements. b): The squeezer has a span of 5.3 THz, with each squeezed line separated by the free spectral range of 210 GHz. The bandwidth of each comb line is of the order of 400 MHz. The analysis cavity on the other hand, has a bandwidth of 5 MHz, with cavity modes separated by 1 GHz.

Here we use self-homodyning via two analysis cavities to demonstrate, for the first time, continuous-variable EPR-type entanglement between bright beams generated from a nanophotonic chip. Building on our recent demonstration, our approach further introduces reflection of the quantum fields from an empty analysis cavity to effectively serve as a self-homodyne mixing with the mean classical field of the respective bright beams, as has been demonstrated off-chip in $\chi^{(2)}$ OPOs [3, 4]. Using this method also offers the advantage of accessing more complex quadrature combinations compared to a local oscillator, by introducing a rotation between the negative and positive noise frequency, on top of applying a global phase to the mean carrier, offering complete Gaussian tomography of two mode squeezed states. While quantum state tomography of a similar nanophotonic silicon nitride OPO above threshold has been recently realized,

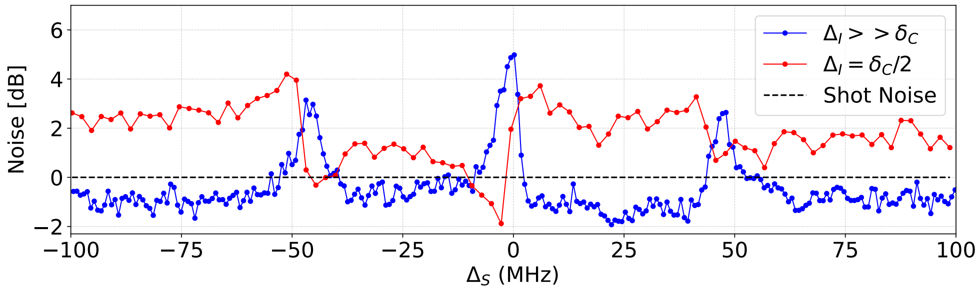

Figure 2: Experimental measurement of two-mode variance for two values of idler cavity detuning Δ_I, as a function of the conjugate signal's cavity detuning Δ_S, accessing respectively amplitude and phase quadratures whose combinations exhibit squeezing and anti-squeezing. The cavities full-width-half-maximum are defined as $\delta_C = 5$ MHz.

thermal effects in the chip were reported, preventing observation of phase squeezing and entanglement [5]. Instead in our work, we harness our seed-assisted OPA below threshold along with analysis cavity detection for Gaussian state tomography, and quantify entanglement using the DGCZ witness. Importantly, this allows us to measure entanglement witnesses for a nondegenerate EPR mode pair with a large frequency separation of 5.37 THz (43 nm).

The experimental setup (Fig. 1.a)) is similar to the one in [2] regarding the seed-assisted nanophotonic OPA for generating squeezed light. Through stimulated parametric amplification, the seed at 1532.34 nm is amplified, and a conjugate signal is generated at 1575.68 nm. In addition to our previous work [2], we send both the amplified seed and the conjugate signal to be reflected off an analysis cavity and then send them towards the two ports of a balanced photodiode. Finally, the noise is measured on an RF spectrum analyzer. The free spectral range of the analysis cavities and their linewidth is measured to be 1.5 GHz and $\delta_C =$ 5 MHz respectively. Piezoelectric stacks attached to the one of the bow-tie cavity mirrors allow to control and sweep their resonance frequency with respect to the seed and conjugate signal's mean field carrier frequency. The cavities replace the need for a local oscillator, by differentially phase-shifting the quantum noise sidebands with respect to the mean field, effectively rotating the noise ellipse of the optical modes [4]. Thus, the phase noise is converted into intensity noise of the beam, which can be directly detected by the photodetector. Fig. 2 shows the experimental results. The blue plot corresponds to the signal cavity scan when the idler cavity is far detuned from the idler field. In this case, at both ends of the scan, the intensity difference exhibits amplitude squeezing. When the signal cavity detuning is set to Δ_S=0, the measured noise increases up to 4.5 dB above the shot noise level. The red plot shows a similar scan, but with the idler cavity set to a fixed detuning of $\Delta_I = \delta_C/2$. At the beginning and end of this scan, the photodiode records amplitude noise on one port and phase noise on the other. Since they are uncorrelated, it leads to a noise higher than shot noise. The most interesting behavior is observed when $\Delta_S = -\delta_C/2$, whereby we observe noise below the shot noise level, corresponding to phase-sum squeezing. Conversely, when $\Delta_S = \delta_C/2$, we observe phase-difference anti-squeezing.

We measure values of amplitude and phase squeezing of respectively $\Delta^2 P_- = 0.72 \pm 0.04$ and $\Delta^2 Q_+ = 0.65 \pm 0.08$ and detect entanglement between the two conjugate variable by violating the continuous-variable entanglement witness of Duan-Giedke-Cirac-Zoller, expressed as

$$\Delta^2 P_- + \Delta^2 Q_+ < 2 = 1.30 \pm 0.12 < 2. \tag{1}$$

In summary, we have generated and measured EPR-type two-mode squeezing and entanglement from a nanophotonic silicon nitride ring resonator. We measure phase-sum squeezing of 1.9 dB over a two-mode entangled pair separation 5.37 THz. Future work will involve the use of this entanglement as a resource for quantum information tasks.

References

[1] Wang, Z. *et al.* Large-scale cluster quantum microcombs. *Light: Science & Applications* **14**, 164 (2025).

[2] Shen, Y. *et al.* Highly squeezed nanophotonic quantum microcombs with broadband frequency tunability. *arXiv:2505.03734* (2025).

[3] Villar, A. S., Cruz, L. S., Cassemiro, K. N., Martinelli, M. & Nussenzveig, P. Generation of Bright Two-Color Continuous Variable Entanglement. *Physical Review Letters* **95**, 243603 (2005).

[4] Villar, A. S. The conversion of phase to amplitude fluctuations of a light beam by an optical cavity. *American Journal of Physics* **76**, 922–929 (2008).

[5] Alfredo Kögler, R. *et al.* Quantum state tomography in a third-order integrated optical parametric oscillator. *Optics Letters* **49**, 3150 (2024).