Squeezing recovery after detection with a completely free-running local oscillator

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Abstract: We performed the first measurement and recovery of squeezed light using a free-running coherent receiver with a separate laser, 98% of the squeezing was preserved in our method relative to measurements with a shared laser. © 2023 The Author(s)

1. Introduction

Squeezed states of light are crucial resources in a wide range of applications including quantum computing [1], quantum communication [2], and quantum metrology [3]. These states are typically measured using homodyne detection facilitated by a strong beam known as a local oscillator (LO) [4]. However, this conventional approach necessitates a complex locking system to lock the LO phase with the squeezed quadrature [5]. The intricacies of such phase-locking systems can be particularly challenging for practical utilization of squeezed light. For instance, in quantum key distribution (QKD), the use of squeezed light can improve tolerance to excess noise, especially with low reconciliation efficiency [6].

Here, we implemented a digital phase compensation scheme to recover the squeezed and anti-squeezed quadratures after measurement with a free-running LO. Our method utilizes intradyne detection in combination with pilot-aided digital signal processing (DSP) to eliminate the need for phase-locking systems entirely. With this method, we achieve the same level of squeezing (and anti-squeezing) as phase-diverse homodyne detection.

2. Method

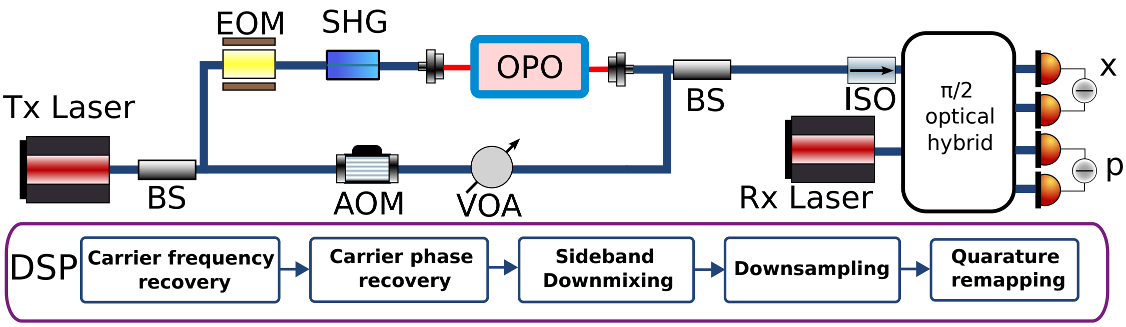

Fig. 1: Experimental setup and digital signal processing (DSP) routine. EOM: electro-optics modulator, SHG: second-harmonic generator, OPO: optical parametric oscillator, AOM: acousto-optics modulator, VOA: variable optical attenuator, BS: beamsplitter, ISO: optical isolator.

Figure 1 shows the experimental setup and the digital signal processing (DSP) chain. At the transmitter, a continuous wave (CW) laser operating at 1550 nm was used as an optical source. The squeezed light is generated using a double resonance optical parametric oscillator (OPO), pumped with a 775 nm light field generated by a second-harmonic generator (SHG) module. An electro-optics modulator (EOM) was used for locking the OPO cavity [4]. The bandwidth of the generated squeezed vacuum was more than $\approx$ 100 MHz [4]. We frequency multiplexed a 40 MHz pilot tone, generated using an acousto-optics modulator (AOM), with the squeezed light to perform receiver DSP on. A variable optical attenuator (VOA) was used to adjust the signal-to-noise ratio of the pilot tone.

At the receiver, we performed intradyne detection using a phase-diverse receiver and a free-running LO, generated by a separate CW laser. This allowed us to access the conjugate quadratures (X and P) simultaneously at the cost of 3 dB of loss. To avoid back reflection, an optical isolator (ISO) was used before the hybrid. Two balanced detectors with a bandwidth of $\approx$ 200 MHz were used to detect the signal. The outputs of the balanced detectors were then digitized at a sample rate of 200 MSample/s. Figure 2 (a) shows the spectrum of the received signals of the X and P detectors, which are a time varying mixture of the squeezed and anti-squeezed quadratures.

To recover squeezing and anti-squeezing, we implemented the offline DSP routine shown in figure 1. The pilot tone was extracted using a bandpass filter with a center frequency computed through the power spectrum of the received signal. The frequency of the pilot tone was estimated through a Hilbert transform of the pilot and a linear fit of the extracted phase profile. The frequency offset between Tx and Rx laser was then estimated as the difference between 40 MHz (the known frequency of modulated pilot tone) and the estimated frequency. This frequency offset was used to correct for frequency drift, as shown in figure 2 (b). To estimate the relative phase between the two lasers, the pilot tone was bandpass filtered and fed into an unscented Kalman filter (UKF) for phase estimation [7]. To measure the squeezing and anti-squeezing at the optimal sideband frequency, the signal was demodulated at 12 MHz after phase compensation. Subsequently, we downsampled the signal such that each squeezing symbol in the ensemble was interpolated from 50 samples, enhancing our estimation of the squeezing information. Finally, the squeezed and anti-squeezed quadrature was aligned by reducing the correlation between squeezing and anti-squeezing in the quadrature remapping module [8].

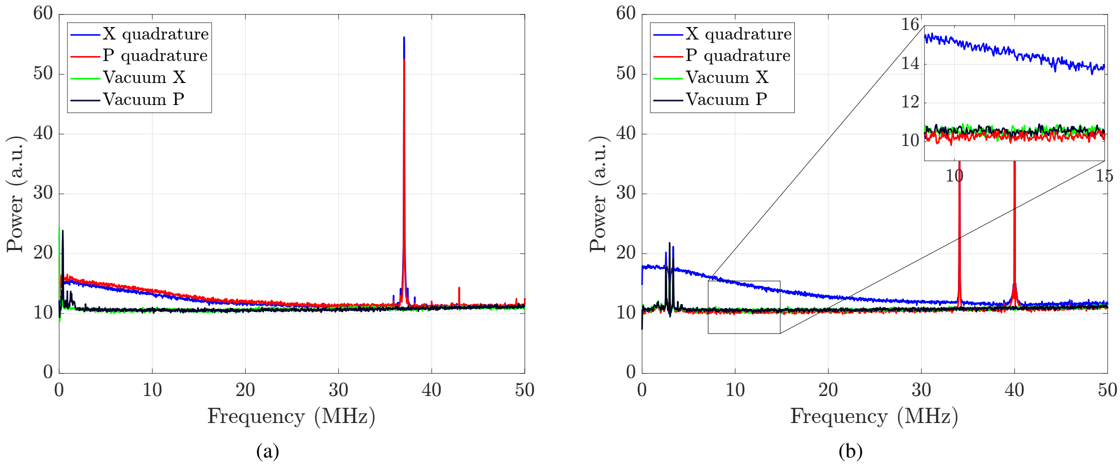

Fig. 2: Spectrum of the signal before and after the DSP procedure. (a) Detected signal before frequency and phase recovery (b) Signal after phase recovery (Inset: frequency range under investigation)

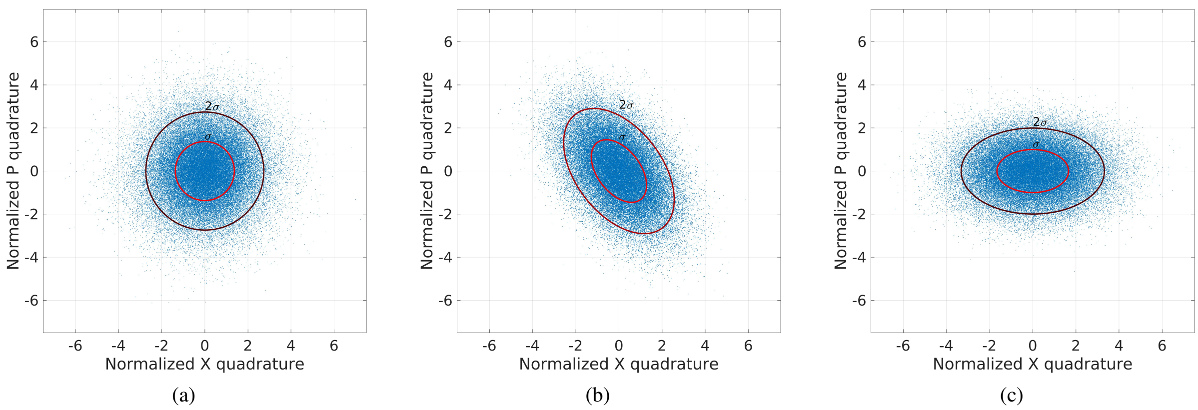

Fig. 3: State ensemble. (a) Before phase recovery; b) After phase recovery; (c) After quadrature remapping

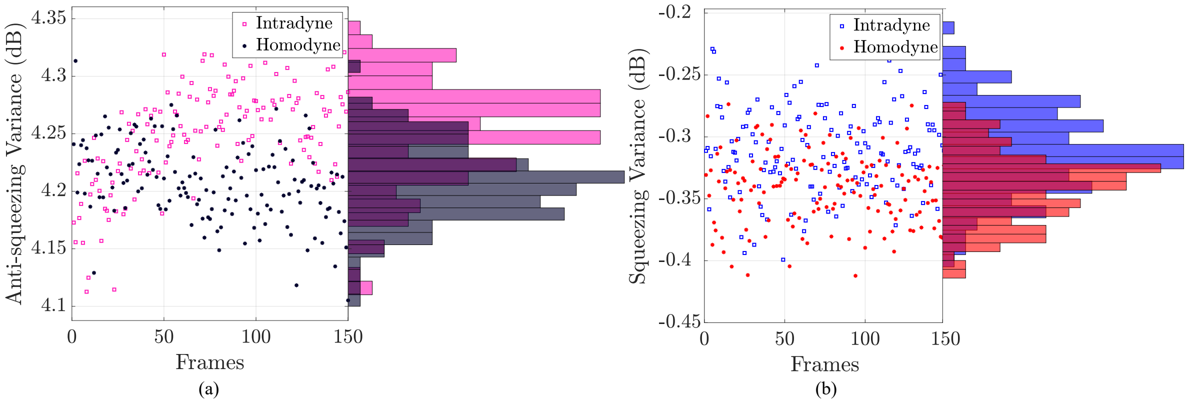

Fig. 4: Squeezed light measurement using carrier phase recovery in comparison with conventional homodyne detection. Each frame consists of 8×10^4 symbols.

3. Results

To illustrate the effectiveness of our post-processing scheme in squeezing recovery, we begin by examining the state ensembles before and after applying our DSP chain as shown in figure 3. The comparison reveals the effectiveness of our DSP chain in mitigating phase noise and aligning the squeezing and anti-squeezing quadratures. Next, we evaluated the performance of our phase compensation scheme by comparing it to conventional phase-diverse homodyne detection with phase locking. To ensure a fair comparison, we used the optical hybrid in both scenarios, along with quadrature remapping to align the squeezing and anti-squeezing quadratures. For simplicity, in the case of homodyne detection, the LO was generated from the transmitter (Tx) laser. Figure 4 (a) shows the squeezing and anti-squeezing levels measured in the intradyne detection case which are ≈ 0.3 dB and ≈ 4.2 dB respectively and figure 4 (b) shows the case of homodyne detection which has the squeezing and anti-squeezing levels of ≈ 0.35 dB and ≈ 4.26 dB. This showed that our method can recover 98% of the squeezing information relative to homodyne detection. The relatively low level of squeezing can be attributed to the low efficiency of the $\pi/2$ optical hybrid, which was measured to be $\approx 31\%$.

4. Conclusion

We successfully retrieved squeezed states of light corrupted by phase noise from free running Tx and Rx lasers, through the use of a phase-diverse intradyne receiver and digitial signal processing. Our results show that we can efficiently recover ≈ 0.3 dB of the squeezing which is 98% in comparison with conventional homodyne detection where the laser source is shared between the transmitter and receiver. Our approach paves the way for simplifying the utilization of squeezed light, particularly in scenarios that extend beyond controlled laboratory environments or remote settings where the deployment of optical phase-locked loops can present formidable challenges. It can be applied to a wide range of squeezed light applications where it is beneficial to measure both light field quadratures simultaneously, such as quantum key distribution and quantum sensing.

Acknowledgments The authors acknowledge support from Innovation Fund Denmark (CryptQ, grant agreement no. 0175-00018A), the Danmarks Frie Forskningsfond (grant agreement no. 0171-00055B), and the DNRF Center for Macroscopic Quantum States (bigQ, DNRF142). AAEH acknowledge support from the Carlsberg Foundation (project CF21-0466). The data was processed using the resources from DTU Computing Center [9].

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