Amplification of a Squeezed-Quadrature using a Cascaded Traveling-Wave Phase-Sensitive Optical Parametric Amplifier

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Abstract: We demonstrate a two-stage system of cascaded traveling-wave phase-sensitive optical parametric amplifiers, achieving 3.6 dB squeezed-quadrature amplification (0.9 dB deamplification) on top of 1.3 dB squeezing provided by the first stage.

1. Introduction

A key goal of research in remote sensing is to maximize resolution in practical systems. It is known that short-wavelength (optical) laser detection and ranging (LADAR) systems offer superior resolution relative to long-wavelength radio-frequency (RF) systems in clear atmospheric conditions. To improve such LADAR systems beyond the classical Rayleigh-limit of resolution, however, it is necessary to exploit quantum optical effects. Although entangled states can be used to surpass the Rayleigh limit [1], the presence of even a small amount of linear loss drastically impairs the expected performance improvement [2]. Considering that $\sim$100 dB loss is not unusual in a realistic standoff scenario, transmitting entangled states to interrogate a target is counter-productive. Indeed, it was recently proposed that the use of a coherent-state (classical) transmitter in conjunction with a nonclassical receiver could improve LADAR resolution over a classical baseline reference [3, 4]. Because only coherent-state light is used to interrogate the target, this method remains robust in the presence of high propagation losses and weak quasi-Lambertian scattering from the target. All nonclassical processing is restricted to the receiver, wherein losses could be more easily managed. The predicted enhancement arises from two nonclassical features used in tandem in the receiver, namely, squeezed-vacuum injection (SVI) followed by phase-sensitive amplification (PSA), which together can achieve approximately three-fold improvement in resolution [4].

In order to accurately construct a high-resolution image, the signal-to-noise ratio (SNR) must be high for a sufficiently large spatial bandwidth. The field in the entrance pupil of a receiver located in the far field of a target is proportional to the Fourier transform of the target's reflection coefficient. Because of imperfections or deliberate apodization, a typical receiver's acceptance profile is softened in the periphery, thereby presenting a soft aperture to the incoming light which causes preferential attenuation of the higher spatial-frequency components. As a result, vacuum noise infiltrates the attenuated spatial frequencies and deteriorates the SNR. The use of SVI can suppress these vacuum fluctuations and thus recover the lost SNR. Real-world receivers are also imperfect in their efficiency of light detection ($\eta < 1$). Therefore, the advantage gained via SVI would be quickly lost due to the vacuum noise introduced because of imperfect detection, unless a noise-free PSA is used to boost the overall detection efficiency. We have previously reported on the experimental realization of improved resolution with use of PSA to overcome the detection inefficiency limitation [5]. We have also reported on a two-stage OPA chain that allows cascaded amplification/deamplification of a selected signal quadrature [6]. Here we report on the successful demonstration of phase-sensitive manipulations of a squeezed-quadrature in a traveling-wave configuration. Our results support the future realization of a quantum enhanced sensor [3, 4].

2. Experimental Configuration

In Fig.1(a) we show the experimental setup. Light from a telecom-band (1560-nm) continuous-wave (CW) distributed-feedback (DFB) laser is fed into a pulse carver that outputs a 10-MHz train of 160-psec flat-top pulses. These pulses are subsequently amplified by a series of erbium-doped fiber amplifiers (EDFAs) to reach peak powers >2 kW. This pulsed light is then collimated into a free-space beam and focused into a periodically-poled potassium-titanyl-phosphate (PPKTP) crystal for second-harmonic generation (SHG). Conversion efficiencies of

>65% produce a pulse train at 780 nm with >1 kW peak power that is then used to pump the OPA stages. A signal beam is tapped prior to the SHG stage and serves as a local oscillator (LO) for the homodyne detector. A second PPKTP crystal is pumped without an input beam to produce squeezed-vacuum (1st OPA). The LO beam is prevented from interacting with the pump or the squeezed-vacuum pulses in both the OPA stages by sending it through the crystals at a slight angle, by temporally delaying it, and by its orthogonal polarization. The 1560-nm beams are then separated from the pump and the squeezed-vacuum pulses are fed into a third PPKTP crystal (2nd OPA) pumped by the residual SHG beam from the 1st OPA. The pump phase at the 2nd OPA stage can be set to either amplify or deamplify the input. The squeezed-vacuum is separated again from the pump at the output of the 2nd OPA and then mixed with the properly delayed LO in order to perform balanced homodyne detection of the phase-sensitively amplified squeezed-quadrature. An in-house designed op-amp based homodyne receiver provides >50 dB common-mode-rejection ratio (CMRR). Before performing the homodyne detection, we verified that the homodyne receiver is shot-noise limited by observing linear dependence of the noise power on the incident LO power. A usable shot-noise limited dynamic range of 8 dB is observed as shown in Fig.1(b).

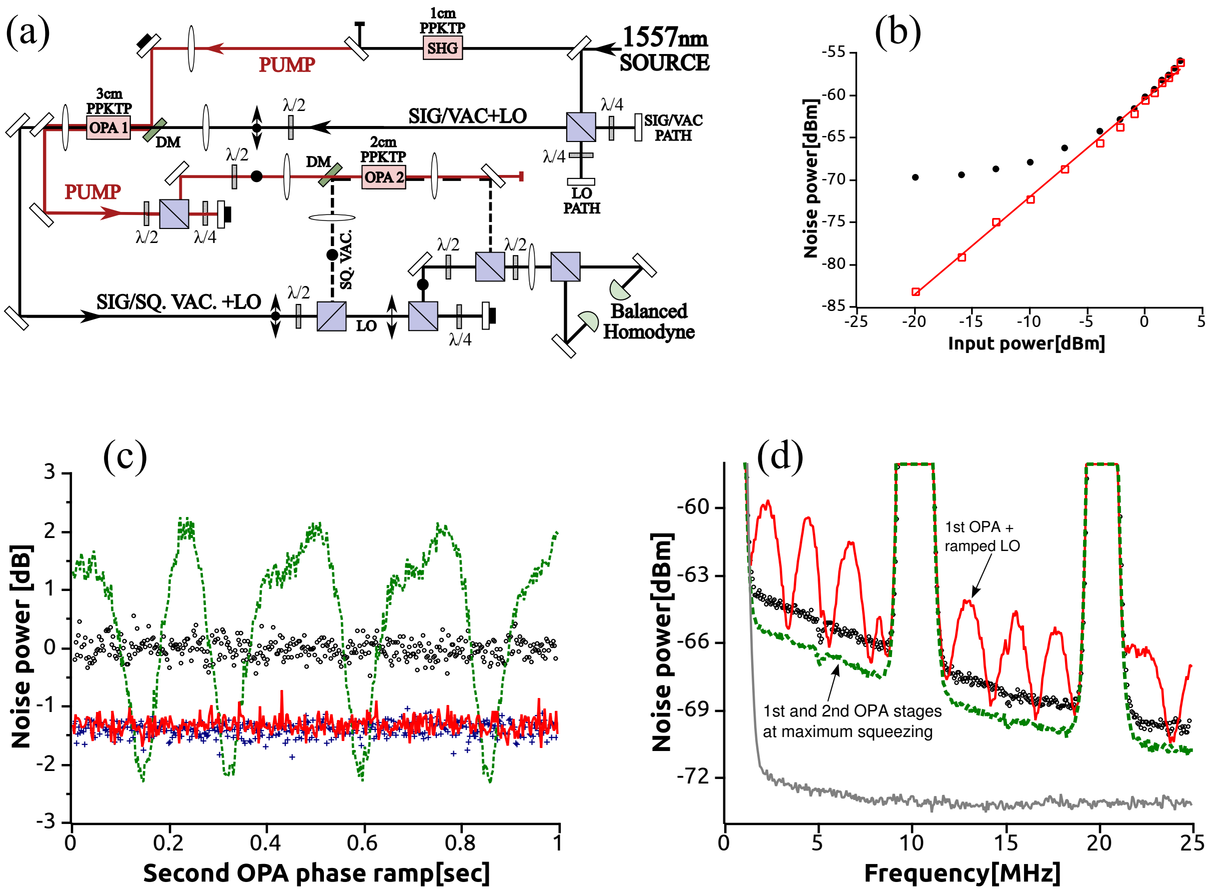

Fig. 1: (Color online) (a) A schematic of the experimental setup. DM: dichroic mirror. (b) Shot-noise linearity test performed at 4 MHz measurement frequency showing 8 dB of dynamic range. Data shown in squares are obtained by subtracting the thermal noise of the homodyne detector from the measured values (circles). (c) Phase-sensitive manipulation of squeezed-vacuum measured at 4 MHz. Open circles: shot-noise level. Solid trace: squeezed-noise power measured by blocking the pump to the 2nd OPA. Pluses: squeezed-noise power measured by blocking the pump to the 1st OPA. Dashed trace: modulation of the squeezed-noise power from the 1st OPA when the phase of the 2nd OPA pump is ramped. (d) Wide-band measurement. Open circles: shot-noise. Solid trace: noise power from the 1st OPA only while the LO phase is ramped. Dashed trace: minimum reduction of noise power achieved when the 2nd OPA is allowed to further squeeze the noise from the 1st OPA. Large peaks are seen at the harmonics of the systems' pulse repition rate. Lowest trace is the homodyne receiver's thermal-noise level.

3. Results

In Fig.1(c) we present the first results of phase-sensitive amplification and deamplification of squeezed light with the cascaded OPA system. Initially, all beams except for the LO are blocked, allowing to establish the shot-noise level of the LO at the measurement frequency. Next, only the 1st OPA is pumped and the resulting squeezed-vacuum is detected in the homodyne receiver, showing a reduction of 1.3 dB in noise power. Lastly, while the LO phase is maintained to measure the squeezed-quadrature, the 2nd OPA is also pumped in order to amplify the squeezed-vacuum entering the 2nd OPA. We ramp the phase of the pump in the 2nd OPA to clearly show both the amplification and deamplificaiton of the squeezed-quadrature. We observed 3.6 dB amplification of the squeezed-vacuum produced by the 1st stage. The cascaded deamplification, however, further squeezes the output from the 1st stage by 0.9 dB. For completeness, we also measured the squeezing level produced in the 2nd OPA stage only. As shown, the squeezing produced in the 2nd stage is similar to the one from the 1st OPA stage. We believe the main reason for the limited observed squeezing in both stages at present can be attributed to poor mode-matching efficiency between the spatio-temporal modes of the Gaussian LO and squeezed-vacuum as well as optical propagation losses. In Fig.1(d) we show a wide-band version of the data shown in Fig.1(c). One sees that the characteristic double-squeezing action performed by the two stages configuration is accessible over a frequency band of at least 20MHz.

4. Conclusion

We have demonstrated a two-stage cascaded OPA system capable of phase-sensitive amplification and deamplification of a squeezed-quadrature. Quantum enhanced LADARs proposed in [4] require SVI followed by PSA, wherein the process of squeezed-quadrature amplification is imperative. The results described above will help faciliate the realization of such enhanced sensors.

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