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Robust and compact entanglement generation from diode-laser-pumped four-wave mixing

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Four-wave-mixing processes are now routinely used to demonstrate multi-spatial-mode Einstein-Podolsky-Rosen entanglement and intensity difference squeezing. Diode-laser-pumped four-wave mixing processes have recently been shown to provide an affordable, compact, and stable source for intensity difference squeezing, but it was unknown if excess phase noise present in power amplifier pump configurations would be an impediment to achieving quadrature entanglement. Here, we demonstrate the operating regimes under which these systems are capable of producing entanglement and under which excess phase noise produced by the amplifier contaminates the output state. We show that Einstein-Podolsky-Rosen entanglement in two mode squeezed states can be generated by a four-wave-mixing source deriving both the pump field and the local oscillators from a tapered-amplifier diode-laser. This robust continuous variable entanglement source is highly scalable and amenable to miniaturization, making it a critical step toward the development of integrated quantum sensors and scalable quantum information processors, such as spatial comb cluster states. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4947026]

Continuous-variable (CV) entangled light sources are critical to optical quantum computation,[1–4] ultra-trace sensing,[5] and high resolution spectroscopy.[6,7] In particular, one-way quantum computation relies on sequential adaptive measurements on each mode of a highly entangled cluster state.[8] A growing number of researchers have demonstrated CV entanglement as a potential resource for quantum computation with four-wave-mixing (4WM) processes[9,10] and optical parametric oscillators.[2,3,11,12] CV cluster states are a promising resource for one-way quantum computing due to the capability to generate entanglement deterministically.[2,13,14] Notably, 10 000 time-multiplexed CV modes were recently sequentially entangled into a dual rail cluster state[2] and more than 60 modes were simultaneously entangled in a frequency comb cluster state, with the promise of thousands of additional modes available.[3] In addition, a recent proposal suggested that the highly multi-spatial-mode squeezed states generated by 4WM could enable a spatial-comb analogue to the frequency-comb cluster state,[4] while other quantum networks involving multiparty correlations have yielded promising results.[15,16] An encoding scheme describing a fault tolerance threshold of 20.5 dB in CV one-way quantum computation has also recently been published.[1] With this growing interest in highly scalable cluster states for one way quantum computation,[1–4] a compact and robust platform capable of scaling entanglement to many modes is increasingly critical. Further, CV systems are becoming increasingly important as quantum sensing platforms. An integrated squeezed light source is critical to deploying current proof of principle quantum sensors[17–19] to the field.

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4WM processes in atomic vapors[20,21] are attractive because of the ease of accessing individual spatial modes and because of the notable squeezing that has already been observed in separable spatial modes.[22,23] A composite detection efficiency exceeding 99% would be necessary to achieve the current fault tolerance threshold, but 4WM experiments have exhibited nearly detection-efficiency-limited squeezing of 8.8–9.2 dB already,[24,25] and cascaded gain regions may enable further increases in squeezing.[16] Diode laser pumped 4WM platforms have been used in recent years to generate the intensity difference squeezing[26] and tapered amplifiers pumped by Ti:sapphire lasers have been used as the pump fields in four-wave mixing processes generating single beam quadrature squeezing.[27] However, the probe fields[26] and local oscillators[27] used in these experiments were not derived from the tapered-amplifier (TA) because of concerns over amplitude noise, and it has remained unknown if excess phase noise produced in the amplifier would prevent bipartite entanglement in these systems. Here, we demonstrate bipartite Einstein-Podolsky-Rosen (EPR) entanglement in a 4WM platform pumped by a master oscillator power amplifier (MOPA) based on a TA chip and a diode-laser pump. Further, we outline the MOPA parameters at which the optimal entanglement is achieved and those for which excess phase noise begins to contaminate the output state and diminish the observable entanglement. Notably, this excess phase noise does not contaminate the relative phase between the local oscillator and signal at the homodyne detector, but rather results in a much higher observed noise level in the phase quadratures of the signal fields.

Replacing the Ti:sapphire pump laser typically used in these experiments with a diode MOPA provides a more affordable and integrable platform. As demonstrated here,

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the complete MOPA offers a form factor nearly an order of magnitude smaller in size than the typical Ti:sapphire lasers, with nearly an order of magnitude smaller acquisition cost. Combining the already-integrable pump source with microfabrication techniques for integrated vapor cell-based sensors[28,29] will result in a fully portable, low cost quantum sensor. The platform also has a highly scalable power output that will be critical to spatially multiplexing cluster states for one-way quantum computation. Indeed, by cascading multiple TAs, it is possible to maintain a chain of spatially separated, high power, phase locked pump lasers and spatially multiplex the 4WM process across many pump and probe fields, resulting in arbitrary scaling of the number of entangled modes, with only a nominal increase in the experimental form factor.

It has been previously shown that the 4WM process in hot ^{85}Rb vapor serves as a phase-insensitive amplifier that generates the CV bipartite entangled probe and conjugate fields a and b.[9,10] The joint variances of the quadrature operators $\hat{X}_a, \hat{Y}_a, \hat{X}_b$, and $\hat{Y}_b$ lead to entanglement witnesses (see supplementary material[30]):

$$\hat{X}_- = \hat{X}_a(t) - \hat{X}_b(t) = [\hat{X}_a(0) - \hat{X}_b(0)]e^{-\kappa t}, \tag{1}$$

$$\hat{Y}_+ = \hat{Y}_a(t) + \hat{Y}_b(t) = [\hat{Y}_a(0) + \hat{Y}_b(0)]e^{-\kappa t}, \tag{2}$$

where the variances are taken relative to the shot noise level (SNL) for each joint quadrature. Here, κ is related to the gain for a given pump field as $\sqrt{G} = \cosh(\kappa t)$, and the entanglement witnesses coincide with the bipartite EPR operators.[31] For gain greater than unity, $\langle \hat{X}_-^2 \rangle = \langle \hat{Y}_+^2 \rangle$ are both squeezed below the SNL. Squeezing in both quadratures for the twin beams studied here is sufficient to prove CV inseparability according to the Duan criterion,[32] which can be quantified as

$$I = \langle \hat{X}_-^2 \rangle + \langle \hat{Y}_+^2 \rangle \tag{3}$$

in terms of shot noise units. When $I < 2$, the states are inseparable. However, the EPR criterion, critical to many quantum information processing protocols, sets a higher bar for entanglement than Eq. (3). The EPR criterion is defined in terms of the conditional variances of the system $V_{X_a|X_b}$ and $V_{Y_a|Y_b}$ as[31] (also see the supplementary material[30]):

$$\epsilon_{ab} = V_{X_a|X_b} V_{Y_a|Y_b} < 1. \tag{4}$$

However, the inequality

$$V_{X_a|X_b} V_{Y_a|Y_b} \leq 4 \langle \Delta \hat{X}_-^2 \rangle \langle \Delta \hat{Y}_+^2 \rangle < 1 \tag{5}$$

enables the calculation of the upper bound on ϵ_{ab} without the need to measure the full conditional variances.[31]

The entanglement generation shown experimentally here relies on a 2 W semiconductor TA pumped by an unlocked (in terms of frequency and phase), temperature controlled 17.7 mW diode laser with a linewidth of 300 kHz in a master oscillator power amplifier configuration as shown in Fig. 1. When the seed laser (or master oscillator) saturates the TA gain, the TA emission exhibits an identical linewidth to the seed laser. Below saturation, as shown in the left of Fig. 2, significant excess noise is visible in dc intensity difference measurements. Above saturation, RF intensity difference noise measurements displayed in the right of Fig. 2 are shot noise limited, indicating that any excess noise on the TA is within the common mode rejection of the balanced photodiode. While this does not guarantee a pure state, the observation of CV entanglement only requires that the sum of any excess classical noise with the quantum noise is less than the shot noise level. After spatially filtering the TA emission, a 720 mW Gaussian mode was split on a polarizing beamsplitter in order to generate the pump and probe fields used for 4WM as shown in Fig. 1. The 4WM mechanism relies on a double lambda configuration[9,10] in hot ^{85}Rb vapor in which a strong optical pump field blueshifted 0.8 GHz from the F = 2 to D1 excited state transition is mixed with a weak probe field that is redshifted from the pump by 3.045 GHz by an acousto-optic modulator (AOM), resulting in the coherent generation of a conjugate field equally blueshifted from the pump as the probe field is amplified.

When the 4WM process was seeded by a weak probe field (150 μW) and a vacuum conjugate field, 4.5 dB of

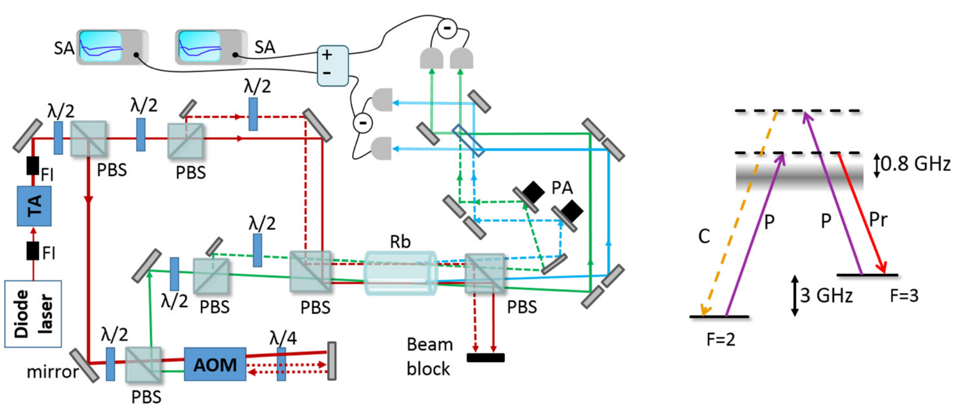

FIG. 1. (Left) Schematic of CV entanglement demonstration. (Diode laser) Newport Vortex II diode laser; (TA) Eagleyard 2 W, 795 nm GaAs tapered amplifier; (FI) Faraday isolator; ($\lambda/2$) half-wave plate; (PBS) polarizing beam splitter; (AOM) acousto-optic modulator; ($\lambda/4$) quarter-wave plate; (Rb) antireflection coated rubidium vapor cell; (PA) piezoelectric actuators; (SA) spectrum analyzers. (Right) Energy level diagram showing a double-Λ system at the D1 line (795 nm) in ^{85}Rb. A large pump (P) amplitude enables a nonlinear gain of order 5 in the probe field, with a conjugate photon (C) coherently emitted for every emitted probe photon (Pr). The shaded region represents the Doppler-broadened excited state, whose hyperfine energy separations are small compared to the Doppler broadening.

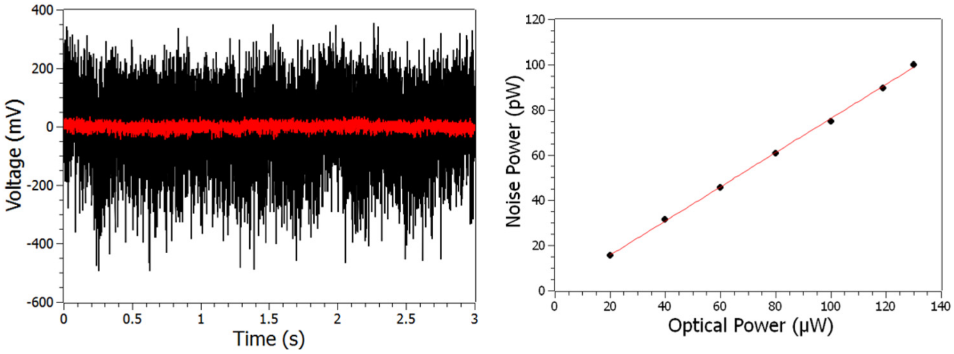

FIG. 2. (Left) DC intensity difference signal just above (red) and below (black) saturation exhibits significant noise reduction upon saturation. (Right) Measured noise in saturated TA exhibits linear dependence on TA power consistent with the optical shot noise.

intensity difference squeezing was observed, consistent with the previous reports of the intensity difference squeezing or amplitude squeezing in TA-pumped 4WM processes.[18,26,27] However, unlike previous reports in which the lower noise diode laser or the Ti:sapphire laser that seeded the TA was used to generate the probe field,[26,27] the probe and pump fields were both derived from the TA. This is critical to applications in which scalable, relative-phase-stable probe power is needed either for high power intensity difference squeezed states or for spatially multiplexed spatial-comb cluster states,[4] as the TA can be used to arbitrarily scale the power in the probe field.

While intensity difference squeezing is the evidence of the presence of quantum correlations, squeezing in the sum and difference of the quadrature signals is necessary to prove the presence of CV entanglement. As shown in Fig. 1, the pump and probe fields were split immediately before the vapor cell in order to generate local oscillators with which to perform dual homodyne detection. Because the local oscillators were derived from the same source as the pump for the vacuum twin beams, phase-stability relative to the signal was achieved without active stabilization. After confirming the overlap of the local oscillator spatial modes with those of the intensity squeezed modes, the weak seed field on the probe channel was blocked in order to measure entanglement between vacuum twin beams with dual homodyne detection. Two piezoelectric actuators were used to simultaneously scan the phase of the local oscillators relative to the vacuum twin beams, and a hybrid junction was used to produce the sum and difference of the quadrature signals measured by the homodyne detectors. Note that both homodyne detectors utilize the same beam splitter, spatially multiplexed for both local oscillators. This spatial multiplexing is critical to the ultimate realization of spatial-comb cluster states.

As shown in Fig. 3(b), this approach yielded at least 3.25 dB of squeezing in both the difference and sum of the quadratures for a TA current just above the gain saturation threshold. For larger TA currents and constant diode laser seed power, the TA acquired excess gain capacity, and the noise in the system quickly increased. Figure 3(a) shows the resulting excess noise present in the local oscillators when the TA current is increased and the gain becomes unsaturated. At the summing output of the hybrid junction, the classical noise of the TA prevents a shot noise measurement, and the squeezing is significantly reduced. At higher currents, no squeezing was observed. However, at the saturation threshold of 2.5 A, the inseparability I as defined in Eq. (3) was given by $I = 0.94 \pm 0.008$. In addition, the EPR parameter ϵ_{ab} at the same current is constrained to be smaller than 0.88 ± 0.004 by Eq. (5), ensuring that we have demonstrated inseparability and EPR entanglement. At the saturation threshold, we also measured the conditional probabilities and obtained a ϵ_{ab} slightly below the upper bound at 0.64 ± 0.004.

It is worth highlighting that continuing to reduce the TA current in order to ensure that the TA was well saturated

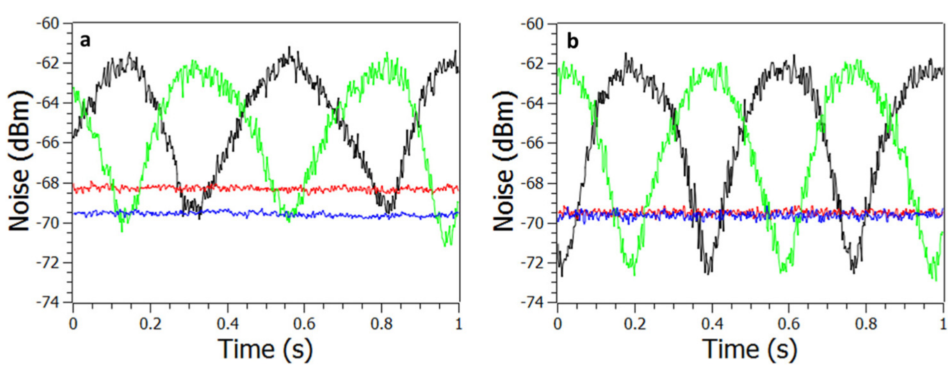

FIG. 3. Quadrature squeezing for differing TA currents. The green and black traces, respectively, show the noise power of the sum and difference of the quadratures measured by the dual homodyne detectors as the local oscillator phases are scanned synchronously. When the two mode squeezed vacuum is blocked, the homodyne detectors record the local oscillator noise, shown in red and blue for the sum and differences of the quadratures, respectively. (a) A TA current of 3 A is below saturation for a 17.7 mW diode pump laser, resulting in minimal squeezing in both quadratures and excess noise in the local oscillators which is observed as excess noise in the summing output of the hybrid junction when the signal port to the HD is blocked. Enough excess noise is present to prevent a shot noise measurement in this case. (b) A TA current of 2.5 A is just above saturation, resulting in 3.25 dB and 3.3 dB of squeezing in the difference and sum of the quadratures measured by the dual homodyne detectors.

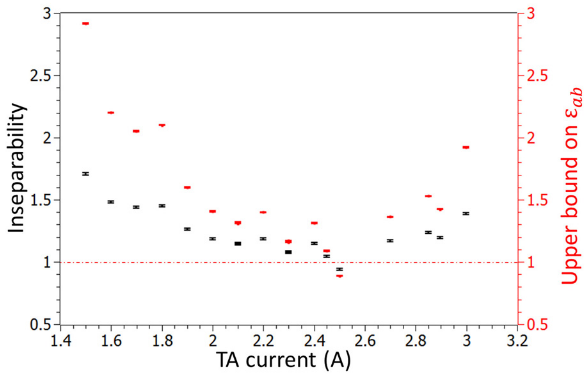

FIG. 4. Inseparability parameter I and upper bound on EPR parameter ϵ_{ab} as a function of TA current illustrate inseparability above and below saturation, but EPR entanglement ($\epsilon_{ab} < 1$) only at 2.5 A.

resulted in a reduced pump power. Figure 4 illustrates the inseparability parameter I for a wide range of TA currents, making it clear that while inseparability persists over the range, the measured noise increases quickly below the saturation threshold (for currents above 2500 mA). In addition, reducing the TA current further reduced the 4WM gain and increased the inseparability parameter. When the input power to the TA was reduced to 15 mW, similar noise properties were observed, with the saturation threshold current commensurately reduced. Inseparability was maintained around the saturation threshold, while EPR entanglement was not observed.

The entanglement illustrated in Figs. 3 and 4, derived entirely from the tapered amplifier output, was stable over a period of roughly an hour on an unfloated optical table in a thermally and mechanically noisy laboratory. The absence of any electronic or cavity locks in this stable and compact system, combined with the capability to scale the output power with daisy-chained TAs, makes this a promising platform for both high power intensity squeezed states and spatially multiplexed spatial-comb cluster states. This combination of environmentally robust operation, scalable power output, and a compact form factor lays the foundation for both one-way quantum computing and fully integrated quantum sensors.

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