Compact diode-laser-pumped quantum light source based on four-wave mixing in hot rubidium vapor

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Using a nondegenerate four-wave mixing process in hot rubidium vapor, we demonstrate a compact diode-laser-pumped system for the generation of intensity-difference squeezing down to 8 kHz with a maximum squeezing of −7 dB. To the best of our knowledge, this is the first demonstration of kilohertz-level intensity-difference squeezing using a semiconductor laser as the pump source. This scheme is of interest for experiments involving atomic ensembles, quantum communications, and precision measurements. The diode-laser-pumped system would extend the range of possible applications for squeezing due to its low cost, ease of operation, and ease of integration.

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Quantum light sources, such as squeezed states and entangled states, are often the fundamental ingredients for high-precision measurements and quantum information. For example, squeezed states with kilohertz sideband frequencies have been applied to gravitational wave detection [1–3], and quantum entangled states have played a critical role in quantum information processing [4].

There are many different approaches to generating quantum light sources [5], and most of them are based on nonlinear processes, such as $\chi^{(2)}$ and $\chi^{(3)}$ processes inside a nonlinear crystal or an atomic vapor cell. Optical parametric oscillators (OPOs) [6–9] and optical parametric amplifiers (OPAs) [10,11] based on a nonlinear crystal inside an optical cavity have become the conventional way to generate quantum light sources.

Many applications of quantum light sources involve subsequent interaction between light and atomic ensembles, as in the case of quantum memory [12,13]. Quantum light sources based on atomic vapors have the advantage that their wavelength and bandwidth naturally match atomic transitions. Recently, it has been shown by Lett's group [14] as well as several other groups [15–17] that the four-wave mixing (FWM) process inside hot rubidium vapor is an efficient way to produce quantum light sources with a large amount of squeezing. Based on this system, the tunable delay [18] and low noise amplification [19] of quantum entanglement have been experimentally demonstrated. Further, with two FWM amplifiers used as a beam splitter and combiner, a nonlinear interferometer with higher phase sensitivity has been constructed [20,21]. Recently, Lvovsky's group [22] has experimentally demonstrated the efficient heralded generation of high-purity narrow-bandwidth single photons using this FWM configuration. Because this FWM scheme can produce correlated twin beams with a large amount of squeezing and maintain squeezing properties at low sideband frequencies, which is useful for the above applications as well as other atom–light interaction studies, it is of interest to develop a compact quantum light source based on this scheme.

To the best of our knowledge, all of the experiments mentioned in [18–20,22] are based on an expensive and bulky Ti:sapphire laser. In contrast, diode lasers are much cheaper, more compact, and easier to operate. They can also address many frequently used atomic transitions in quantum optics and atom optics. These characteristics make diode lasers an ideal candidate for developing an integratable quantum light source. Squeezed states with diode lasers as the pump sources have been demonstrated in OPAs and OPOs [23,24]. In this Letter, we report the construction of a compact diode-laser-pumped quantum light source based on FWM in hot rubidium vapor capable of producing intensity-difference squeezing down to 8 kHz with a maximum of −7 dB.

As shown in Fig. 1, the FWM process relies on a double-Λ scheme in which a conjugate beam is created by mixing a strong pump beam with a weak red detuned seed beam, called the probe. The process is coherent, and the intensities of the probe and conjugate beams are highly correlated with an intensity-difference noise below the shot noise limit (SNL). Our experiment begins with a semiconductor laser that has a linewidth of 100 kHz tuned about 0.8 GHz to the blue of the D1 line of ^{85}Rb ($5S_{1/2}$, $F = 2 \rightarrow 5P_{1/2}$, 795 nm) with a total power of 90 mW. A polarizing beam splitter (PBS) is used to split the beam into two. One of the beams goes through a semiconductor tapered amplifier and is amplified to a power of about 400 mW. The second beam is double-passed in an acousto-optic modulator (AOM) that is driven by a radio frequency (RF) signal generator. In this way, a much weaker seed probe beam (≈30 μW) tuned 3.04 GHz to the red of the pump is derived, which results in very good relative phase stability of the seed probe with respect to the pump. By choosing vertical polarization for the pump and horizontal polarization for the

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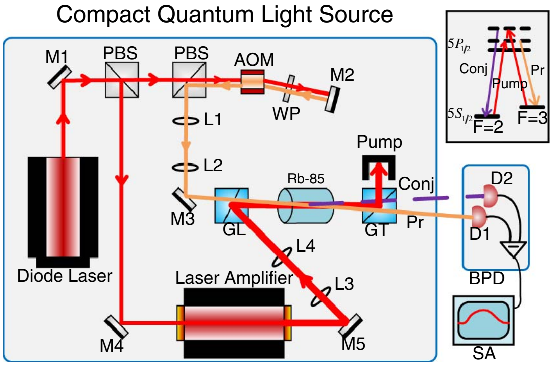

Fig. 1. (Color online) Experimental setup and double-Λ scheme of ^{85}Rb D1 line. M, mirror; L, lens; PBS, polarizing beam splitter; AOM, acoustic-optic modulator; WP, quarter wave plate; GL, Glan–Laser polarizer; GT, Glan–Thompson polarizer; D, detector; BPD, balanced photodetector; SA, spectrum analyzer. Pr, probe, Conj, conjugate.

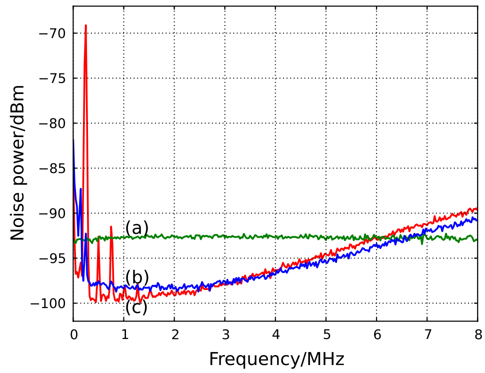

Fig. 2. (Color online) Noise power. (a) SNL, intensity-difference squeezing between the probe and conjugate (b) with and (c) without balancing the intensities of these two beams. 30 kHz RBW and 300 Hz VBW.

seed, they can be combined in a Glan–Laser polarizer. The beams then cross each other at an angle of 0.3° in the center of the isotopically pure ^{85}Rb cell. The vapor cell is 12.5 mm long and temperature stabilized at 121 °C. The pump beam and the seed probe beam are focused with waists of 530 μm and 330 μm ($1/e^2$ radius), respectively, at the crossing point to ensure that they overlap over almost the full length of the cell.

With a 280 mW pump and 15 μW seed as well as the conditions mentioned above, the seed probe signal is amplified to about 123 μW. In the meantime, a conjugate beam tuned 3.04 GHz to the blue of the pump is produced on the other side of the pump beam with an angle that fits the phase-matching condition. Its power is about 111 μW. After the vapor cell, a Glan–Thompson polarizer with an extinction ratio of $10^5:1$ is used to filter out the pump beam. The amplified probe and the generated conjugate beams are directly sent into the two ports of a balanced photodetector (BPD) with a gain of 10^4 V/A and a quantum efficiency of 96%. The output of the BPD is sent to a RF spectrum analyzer with a resolution bandwidth (RBW) of 30 kHz and a video bandwidth (VBW) of 300 Hz. To measure the SNL, a coherent laser beam, whose power is about 234 μW, which is equivalent to the total power of the probe and conjugate, is split into two beams using a 50/50 beam splitter and sent to the BPD.

As shown by curve (c) of Fig. 2, the intensity-difference squeezing spans a frequency range of 6 MHz and the maximum squeezing is −7 dB at 0.85 MHz. Several peaks appear at sideband frequencies 256 kHz and its second, third, and fourth harmonic frequencies. It is found that these peaks originate from the RF signal generator we use. To eliminate these peaks, we balance the intensities of the probe and conjugate beams by attenuating the probe. As shown in curve (b) of Fig. 2, these peaks can be eliminated well at the expense of reducing the maximum squeezing to −5.7 dB at 0.85 MHz, and meanwhile, the squeezing bandwidth increases from 6 MHz to 6.7 MHz. Curves (b) and (c) have a crossing point around 3 MHz, which gives about −5 dB squeezing. The plots in Fig. 2 show that attenuating one of the twin beams in order to balance them is not necessary to achieve maximum squeezing, but it reduces the squeezing at lower frequencies even as it helps cancel the noise peaks. This would be a counterintuitive result for twin beam output from an OPO, which amplifies vacuum inputs, but it is understandable when the noise of the input probe in FWM is considered. If the probe is not shot noise limited, the output difference signal will show the noise of the input field. Balancing the beams to remove the classical noise also reduces the quantum correlations, because photons are removed at random from each beam.

Normally, the diode laser is more noisy than a Ti:sapphire laser. To investigate how the excess noise of the diode laser affects the degree of squeezing, we vary the seed probe power and record the intensity-difference noise power versus the total power of the twin beams at 635 kHz. We do the same for the SNL (Fig. 3). Both the FWM and SNL noise power curves fit to straight lines, with a ratio of slopes equal to 0.213 = −6.7 dB.

We next investigate the squeezing properties in the low frequency region by scanning the two-photon detuning. The lowest squeezing frequency is achieved by setting the two-photon detuning to 14 MHz. We use a real-time spectrum analyzer whose bandwidth spans from 1 Hz to 8 GHz. The RBW of the spectrum analyzer is set to 200 Hz for this measurement. As shown in Fig. 4, with a 70 μW probe and a 64 μW conjugate, the intensity-difference

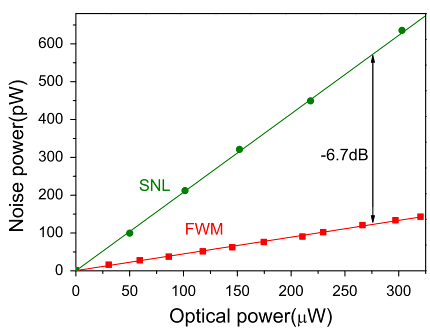

Fig. 3. (Color online) Intensity-difference noise versus total optical power at 635 kHz. Green circles, SNL; red squares, FWM. The ratio of the two slopes is −6.7 dB.

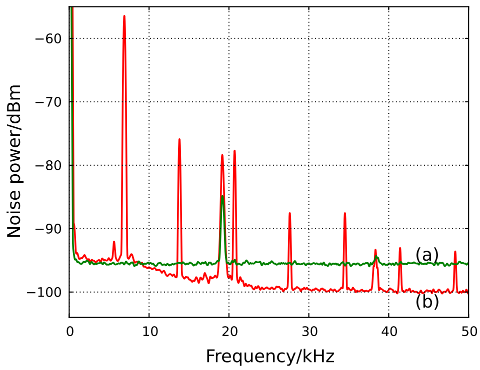

Fig. 4. (Color online) Low-frequency noise power spectrum. (a) SNL and (b) intensity-difference squeezing between the probe and conjugate. 200 Hz RBW.

noise signal above 23 kHz is almost flat at 5 dB below the SNL except for a few peaks. Below 23 kHz, the technical noise of the semiconductor laser starts to dominate, which decreases the level of squeezing, and therefore at frequencies below 8 kHz no squeezing can be observed. To the best of our knowledge, this is the lowest frequency squeezing achieved with a diode-laser-pumped system. Based on this result, a diode-laser-pumped system for the transfer of optical squeezing onto matter waves [25] is feasible.

In conclusion, using a compact diode-laser-pumped system, we have experimentally demonstrated the generation of low-frequency, strong-intensity-difference squeezing of −7 dB based on a FWM amplifier in hot ^{85}Rb vapor. Squeezing down to 8 kHz near the D1 line of rubidium shows great potential for precision measurements and quantum information. Compared with nonclassical light directly generated using laser diodes [26], our system can generate two mode quantum correlations or entanglement, which promises much more broad applications [18–22]. The diode-laser-pumped system would extend the range of possible applications for squeezing due to its low cost, ease of operation, and ease of integration.

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