Strong relative intensity squeezing by 4-wave mixing in Rb vapor

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We have measured -3.5 dB (-8.1 dB corrected for losses) relative intensity squeezing between the probe and conjugate beams generated by stimulated, nondegenerate four-wave mixing in hot rubidium vapor. Unlike early observations of squeezing in atomic vapors based on saturation of a two-level system, our scheme uses a resonant nonlinearity based on ground-state coherences in a three-level system. Since this scheme produces narrowband, squeezed light near an atomic resonance it is of interest for experiments involving cold atoms or atomic ensembles. © 2018 Optical Society of America

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Twenty years ago, the pioneering work of Slusher, et al. led to the first experimental demonstration of a squeezed state of light, using four-wave mixing (4WM) in sodium vapor. Since that time, many groups have demonstrated squeezing based on 4WM in atomic vapors under a variety of different conditions.

Despite the breadth of these experimental results, 4WM in atomic vapors has never generated large amounts of squeezing. To our knowledge, the highest reported level of squeezing from atomic-vapor 4WM is -2.2 dB, using cold atoms in a cavity. This is in marked contrast to systems based on 4WM in optical fibers, for which relative intensity squeezing of up to -4.6 dB (-10.3 dB after loss correction) has been observed. Systems based on parametric down-conversion (PDC) have been even more successful, generating better than -9 dB (measured) of relative intensity squeezing.

It has been suggested that squeezing from 4WM in atomic vapors is limited by spontaneous emission noise when the nonlinearity is based on coherences between levels separated by optical transitions. A large number of recent experiments have demonstrated the power of atomic-vapor 4WM using nonlinearities based on ground-state coherences, in which coherent population trapping and electromagnetically induced transparency (EIT) can reduce or eliminate spontaneous emission noise. Of particular relevance to this work, classical noise correlations in such a Λ system were measured in sodium vapor and 4WM in this system was predicted to generate squeezing. Approximately -0.2 dB of squeezing has been demonstrated in a Λ system in rubidium vapor.

Inspired by these results and motivated by the desire to produce correlated photons that can interact with laser-cooled atoms to produce correlated atom-optical beams we have revisited the question of squeezing generated by 4WM in atomic vapors. In this Letter, we report the demonstration of -3.5 dB (-8.1 dB corrected) of relative intensity squeezing between the probe and conjugate beams produced in a seeded, nearly copropagating, nondegenerate 4WM scheme in hot rubidium vapor. Our system does not involve a cavity or cold atoms and has a single-pass net optical gain of only ~ 4. We anticipate that further experimental improvements to the system could produce significantly greater squeezing, perhaps making atomic-vapor 4WM competitive with optical fibers and PDC-based systems as a source of squeezed light.

Our experiment begins with two Ti:Sapphire lasers tuned to the D1 line of rubidium (795 nm). We use 350 mW of light from one as a pump beam, and up to 0.2 mW of light from the other as a probe. We combine the pump and probe beams with crossed linear polarizations and send them into a natural-abundance rubidium vapor cell heated to 125 C (atomic density ~ 3 x 10^{13} cm^{-3}) with no magnetic shielding. The beams cross at a small angle (~0.75 degrees) and the cell is tilted at Brewster’s angle (~8 mm path length) to minimize reflection losses for the probe polarization. (See Fig. 1.) The pump beam waist is 600 μm while the probe beam waist is 350 μm. After the cell the pump beam is filtered out using a Glan-Taylor polarizer, with a dis-
crimination of \( \sim 10^3 : 1 \).

With the pump detuned \( \sim 1 \) GHz to the blue of the \( ^85\text{Rb} F=2 \rightarrow F' \) transition, we scan the probe by 12 GHz across the D1 line and observe a number of transmission features (see Fig. 1). The most prominent are two probe intensity gain peaks, at the \( ^85\text{Rb} \) ground-state hyperfine splitting of 3 GHz to the red and blue of the pump detuning. These are due to forward 4WM gain. The probe gain is accompanied by the generation of a conjugate beam with detuning from the pump opposite to that of the probe, polarization parallel to the probe, and propagation direction at the same pump-probe angle but on the opposite side of the pump. The slight dispersive character of the redder of the two 4WM gain features is caused by a competition between Raman absorption, EIT, and the 4WM gain. The absorptive feature at -2.5 GHz is 6.8 GHz to the red of the pump detuning, and is due to Raman absorption in the \( ^87\text{Rb} \) atoms.

In order to measure the relative intensity noise between the probe and conjugate, we switch to a phase-locked probe beam of the same waist, generated by double-passing a small fraction of the pump light through a 1.5 GHz acousto-optic modulator. We then calibrate the standard quantum limit (SQL) “shot noise” of our system by picking off the probe before the cell, splitting it with a 50/50 beamsplitter, and directing the resulting beams into a balanced, amplified photodetector with a transimpedance gain of \( 10^5 \text{V/A} \) and 82% quantum efficiency. We measure the spectrum of electrical noise power of the photodetector output voltage on a spectrum analyzer set to a 300 kHz resolution bandwidth and a 100 Hz video bandwidth. The balanced detection technique subtracts away common-mode noise to better than 25 dB. The balanced photodetector noise level is a measure of the SQL for the total amount of optical power arriving at the photodetector. The shot noise should be independent of frequency, which is indeed the case within the bandwidth of our detection electronics, which begins to roll off above 3 MHz. For a total power of 180 \( \mu \text{W} \) (90 \( \mu \text{W} \) out of each port) the measured SQL is -68 dBm (see Fig. 2).

Next, with a pump detuning of 750 MHz and the probe tuned 3.03 GHz to the red, the light is redirected through the atoms. Under these conditions the probe has a gain \( g = 4 \). As a seeded process the probe and conjugate should have a power ratio of \( g/(g-1) \). In the absence of the pump, the absorption of the probe is \( \sim 7\% \), while the absorption at the conjugate detuning is negligible. Due to this differential absorption the probe and conjugate emerge from the cell with the same power to within 10%. We direct these beams onto the balanced photodetector and measure the noise-power spectrum. For a total optical power (probe plus conjugate) of 180 \( \mu \text{W} \), the noise power is as much as 3.5 dB below the SQL for frequencies from 300 kHz to \( \sim 4 \) MHz (see Fig. 2).

To better quantify the degree of squeezing we measure the relative probe-conjugate noise power at 1 MHz as a function of the total optical power impinging on the photodetector, and compare it with the 50/50 beamsplitter SQL measurement as described above, for various powers (see Fig. 3). Fitting both the 4WM and SQL noise power curves to straight lines, we find that the probe and conjugate relative intensity noise is 3.5 dB below the SQL. Using a model for twin-beam losses, we correct for our detector efficiency (82%) and the transmission of the optical path from the atoms to the detector (80%), resulting in a noise power 8.1 \( \pm 1.4 \) dB below the SQL before the exit window of the cell. This is limited by both the (asymmetric) absorption in the cell and the imbalance due to the injected probe light.

We next measure the noise properties of the individual probe and conjugate beams after the cell, by blocking one and then the other. The resulting noise spectra are nearly identical, and show increased noise above the SQL (see Fig. 3). Since the probe and conjugate alone have only half the total optical power, the correct SQL with which to compare them is lower by 3 dB (-71 dBm), since SQL noise power scales linearly with optical power. At 1 MHz the probe and conjugate alone each have 7.6 times more noise than the SQL. The net probe intensity gain is 4 at the end of the vapor. If the 4WM system were operating as a perfect quantum-noise-limited amplifier with this gain (and correcting for losses) we would expect only 4.9 times the SQL with a shot-noise-limited input probe.

As a final experimental check, we tune the probe 3.03 GHz to the blue of the pump, coinciding with the blue 4WM gain peak. For this configuration the probe
and conjugate display relative intensity noise reduction of only about 2.5 dB. This is consistent with the fact that the conjugate beam now experiences more absorption than the probe, leading to less well-balanced optical powers on the detector. Both fits are to straight lines.

Our 4WM configuration is related to that discussed by Lukin and coworkers, with probe and conjugate photons playing complementary roles in the atomic preparation and photon scattering from the atomic coherence. Previous experiments working with the $\Lambda$ scheme have tended to operate at low power and near resonance. The experiments reported here, however, operate in a different regime and combine a number of features used individually in previous investigations of $\Lambda$ systems, including a nearly copropagating geometry, a very large Rabi frequency for the pump laser ($\Omega_{\text{pump}} \approx 100\, \text{GHz}$), and a large detuning. Furthermore, the choice of cross-polarization of the pump and probe reduces the reabsorption, since it leads to optimal EIT on the D1 line of rubidium by creating a dark state that simultaneously satisfies multiple $\Lambda$ transitions.

The phase stability of the pump and probe beam appears to be an important but not critical issue; we were able to observe nearly the same amount of squeezing by using independent pump and probe lasers, although with a phase-locked pump and probe the spectrum of squeezing was extended to lower frequencies by about 250 kHz. We intend to explore further EIT improvements with magnetic shielding and buffer gases, as well as single-isotope cells of $^{85}\text{Rb}$, which should allow us greater freedom in detuning. In addition, by pumping on the transitions that we used here as the probe and conjugate, it should be possible to produce degenerate twin beams and quadrature squeezing. These photons would be narrowband and at a frequency required for cold atom experiments.

In conclusion, we have measured -3.5 dB (-8.1 dB corrected for losses) relative intensity squeezing in forward

four-wave-mixing in hot atomic vapor, in a simple system without a cavity or feedback loops. This system promises to be an important source of narrowband squeezed light near atomic transitions.

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References

1. R.E. Slusher, L.W. Hollberg, B. Yurke, J.C. Mertz, J.F. Valley, Phys. Rev. Lett. 55, 2409 (1985).
2. M.W. Maeda, P. Kumar, J.H. Shapiro, Opt. Lett. 12, 161 (1987); L.A. Orozco, M.G. Raizen, M. Xiao, R.J. Brecha, H.J. Kimble, J. Opt. Soc. Am. B 4, 1490 (1987); M.G. Raizen, L.A. Orozco, M. Xiao, T.L. Boyd, H.J. Kimble, Phys. Rev. Lett. 59, 198 (1987); M. Vallet, M. Pinard, G. Gryenberg, Europhys. Lett. 11, 739 (1990); S.T. Ho, N.C. Wong, J.H. Shapiro, Opt. Lett. 16, 840 (1991); D.M. Hope, H.-A. Bachor, P.J. Manson, D.E. McClelland, P.T.H. Fisk, Phys. Rev. A 46, R1181 (1992); V. Josse, A. Dantan, L. Vernac, A. Bramati, M. Pinard, E. Giacobino, Phys. Rev. Lett. 91, 103601 (2003); J. Ries, B. Brezger, A.I. Lvovsky, Phys. Rev. A 68, 025801 (2003); M.T.L. Hsu, G. Hé tét, A. Peng, C. Harb, H.-A. Bachor, M.T. Johnson, J.J. Hope, P.K. Lam, A. Dantan, J. Cviklinski, A. Bramati, M. Pinard, Phys. Rev. A 73, 023806 (2006).
3. A. Lambrecht, T. Coudreau, A.M. Steinberg, E. Giacobino, Europhys. Lett. 36, 83 (1996).
4. K. Hirosawa, H. Furumochi, A. Tada, F. Kannari, Phys. Rev. Lett. 94, 203601 (2005).
5. S. Feng, O. Pfister, Phys. Rev. Lett. 92, 203601 (2004).
6. J. Laurat, L. Longchambon, C. Fabre, T. Coudreau, Opt. Lett. 30, 1177 (2005).
7. R.E. Slusher, L. Hollberg, B. Yurke, J.C. Mertz, J.F. Valley, Phys. Rev. A 31, 3512 (1985).
8. T.T. Grove, M.S. Shahriar, P.R. Hemmer, P. Kumar, V.S. Sudarshanam, M. Cronin-Golomb, Opt. Lett. 22, 769 (1997).
9. M. Shahriar, P. Hemmer, Opt. Comm. 158, 273 (1998).
10. M. Lukin, P. Hemmer, M. Löffler, M. Scully, Phys. Rev. Lett. 94, 2675 (1998); M. Lukin, A. Matsko, M. Fleischhauer, M. Scully, Phys. Rev. Lett. 82, 1847 (1999).
11. C.H. van der Wal, M.D. Eisaman, A. André, R.L. Walsworth, D.F. Phillips, A.S. Zibrov, M.D. Lukin, Science 301, 196 (2003).
12. P.D. Lett, J. Mod. Opt. 51, 1817 (2004).
13. S. Haine, J. Hope, Phys. Rev. A 72, 033601 (2005).
14. O. Aytür, P. Kumar, Phys. Rev. Lett. 65, 1551 (1990).
15. D. Smithey, M. Beck, M. Belsley, M. Raymer, Phys. Rev. Lett. 69, 2650 (1992).
16. T. Zanon, S. Guerandel, E. de Clercq, D. Holleville, N. Dimarcq, A. Clairon, Phys. Rev. Lett. 94, 193002 (2005).

Fig. 3. Relative intensity noise at 1 MHz for: (A) a 50/50 beamsplit probe with no atoms, and (B) the 4WM configuration, both vs. total power falling on the photodetector. Both fits are to straight lines.