Quantum correlated light beams from non-degenerate four-wave mixing in an atomic vapor: the D1 and D2 lines of ^{85}Rb and ^{87}Rb

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Abstract: We present experimental results showing that quantum correlated light can be produced using non-degenerate, off-resonant, four-wave mixing (4WM) on both the D1 (795 nm) and D2 (780 nm) lines of ^{85}Rb and ^{87}Rb, extending earlier work on the D1 line of ^{85}Rb. Using this 4WM process in a hot vapor cell to produce bright twin beams, we characterize the degree of intensity-difference noise reduction below the standard quantum limit for each of the four systems. Although each system approximates a double-lambda configuration, differences in details of the actual level structure lead to varying degrees of noise reduction. The observation of quantum correlations on light produced using all four of these systems, regardless of their substructure, suggests that it should be possible to use other systems with similar level structures in order to produce narrow frequency, non-classical beams at a particular wavelength.

OCIS codes: (270.6570) Squeezed states; (230.4320) Nonlinear optical devices

References and links

1. R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley, "Observation of squeezed states generated by four-wave mixing in an optical cavity," Phys. Rev. Lett. **55**(22), 2409–2412 (1985).
2. A. Lambrecht, T. Coudreau, A. M. Steinberg, and E. Giacobino, "Squeezing with cold atoms," Europhys. Lett. **36**(2), 93–98 (1996).
3. D. A. Braje, V. Balić, S. Goda, G. Y. Yin, and S. E. Harris, "Frequency mixing using electromagnetically induced transparency in cold atoms," Phys. Rev. Lett. **93**(18), 183601 (2004).
4. B. Julsgaard, J. Sherson, J. I. Cirac, J. Fiurásek, and E. S. Polzik, "Experimental demonstration of quantum memory for light," Nature **432**(7016), 482–486 (2004).
5. I. Novikova, A. V. Gorshkov, D. F. Phillips, A. S. Sørensen, M. D. Lukin, and R. L. Walsworth, "Optimal control of light pulse storage and retrieval," Phys. Rev. Lett. **98**(24), 243602 (2007).
6. K. Honda, D. Akamatsu, M. Arikawa, Y. Yokoi, K. Akiba, S. Nagatsuka, T. Tanimura, A. Furusawa, and M. Kozuma, "Storage and retrieval of a squeezed vacuum," Phys. Rev. Lett. **100**(9), 093601 (2008).
7. G. Hètet, B. C. Buchler, O. Glöeckl, M. T. L. Hsu, A. M. Akulshin, H. A. Bachor, and P. K. Lam, "Delay of squeezing and entanglement using electromagnetically induced transparency in a vapour cell," Opt. Express **16**(10), 7369–7381 (2008).
8. G. Hétet, O. Glockl, K. A. Pilypas, C. C. Harb, B. C. Buchler, H. A. Bachor, and P. K. Lam, "Squeezed light for bandwidth-limited atom optics experiments at the rubidium D1 line," J. Phys. B **40**(1), 221–226 (2007).
9. S. W. Du, J. M. Wen, and M. H. Rubin, "Narrowband biphoton generation near atomic resonance," J. Opt. Soc. Am. B **25**(12), C98 (2008).
10. S. A. Haine, and J. J. Hope, "Outcoupling from a Bose-Einstein condensate with squeezed light to produce entangled-atom laser beams," Phys. Rev. A **72**(3), 033601 (2005).
11. P. D. Lett, "Correlated photons for correlated atoms," J. Mod. Opt. **51**, 1817 (2004).
12. C. F. McCormick, A. M. Marino, V. Boyer, and P. D. Lett, "Strong low-frequency quantum correlations from a four-wave-mixing amplifier," Phys. Rev. A **78**(4), 043816 (2008).
13. J. Laurat, L. Longchambon, C. Fabre, and T. Coudreau, "Experimental investigation of amplitude and phase quantum correlations in a type II optical parametric oscillator above threshold: from nondegenerate to degenerate operation," Opt. Lett. **30**(10), 1177–1179 (2005).

14. H. Vahlbruch, M. Mehmet, S. Chelkowski, B. Hage, A. Franzen, N. Lastzka, S. Goßler, K. Danzmann, and R. Schnabel, "Observation of squeezed light with 10-dB quantum-noise reduction," Phys. Rev. Lett. **100**(3), 033602 (2008).
15. A. M. Marino, R. C. Pooser, V. Boyer, and P. D. Lett, "Tunable delay of Einstein-Podolsky-Rosen entanglement," Nature **457**(7231), 859–862 (2009).
16. R. C. Pooser, A. M. Marino, V. Boyer, K. M. Jones, and P. D. Lett, "Low-noise amplification of a continuous-variable quantum state," Phys. Rev. Lett. **103**(1), 010501 (2009).
17. V. Boyer, A. M. Marino, R. C. Pooser, and P. D. Lett, "Entangled images from four-wave mixing," Science **321**(5888), 544–547 (2008).
18. E. E. Mikhailov, and I. Novikova, "Low-frequency vacuum squeezing via polarization self-rotation in Rb vapor," Opt. Lett. **33**(11), 1213–1215 (2008).
19. C. M. Caves, "Quantum Limits on Noise in Linear-Amplifiers," Phys. Rev. D Part. Fields **26**(8), 1817–1839 (1982).
20. M. S. Shahriar, and P. R. Hemmer, "Generation of squeezed states and twin beams via non-degenerate four-wave mixing in a Λ system," Opt. Commun. **158**(1-6), 273–286 (1998).
21. M. D. Lukin, P. R. Hemmer, M. Löffler, and M. O. Scully, "Resonant enhancement of parametric processes via radiative interference and induced coherence," Phys. Rev. Lett. **81**(13), 2675–2678 (1998).
22. M. D. Lukin, A. B. Matsko, Fleischhauer, and M. O. Scully, "Quantum noise and correlations in resonantly enhanced wave mixing based on atomic coherence," Phys. Rev. Lett. **82**(9), 1847–1850 (1999).
23. M.D. Lukin, P.R. Hemmer, and M.O. Scully, "Resonant nonlinear optics in phase coherent media," in Advances in Atomic, Molecular, and Optical Physics **42**, Elsevier (1999).
24. M. Stähler, R. Wynands, S. Knappe, J. Kitching, L. Hollberg, A. Taichenachev, and V. Yudin, "Coherent population trapping resonances in thermal [85]Rb vapor: D1 versus D2 line excitation," Opt. Lett. **27**(16), 1472–1474 (2002).
25. D. A. Steck, "Rubidium 85 D line data,", *http://steck.us/alkalidata* (revision 0.2 1 September 2008); D.A. Steck, "Rubidium 87 D line data," *http://steck.us/alkalidata* (revision 2.1, 1 September 2008).
26. F. Renzoni, W. Maichen, L. Windholz, and E. Arimondo, "Coherent population trapping with losses observed on the Hanle effect of the D1 sodium line," Phys. Rev. A **55**(5), 3710–3718 (1997).
27. I. Novikova, D. F. Phillips, A. S. Zibrov, R. L. Walsworth, A. V. Taichenachev, and V. I. Yudin, " Comparison of [87]Rb N-resonances for D1 and D2 transitions, " Opt. Lett. **31**(15), 2353 (2006).
28. A. S. Zibrov, C. Y. Ye, Y. V. Rostovtsev, A. B. Matsko, and M. O. Scully, "Observation of a three-photon electromagnetically induced transparency in hot atomic vapor," Phys. Rev. A **65**(4), 043817 (2002).

1. Introduction

Since the early days of research on squeezed states of light [1], it has been appreciated that four-wave mixing (4WM) in an atomic vapor can produce non-classical states of light. Achieving high levels of single mode quadrature squeezing in this way has, however, proved difficult even when cold atoms are used [2]. Despite this, work on 4WM in atomic vapors has continued, particularly as interest has broadened beyond single mode quadrature squeezing to quantum correlations between multiple beams. For example, the use of both cold atoms and electromagnetically induced transparency has opened the way for 4WM production of correlated photons using ultra-low optical powers in an optically thick medium [3]. The development of "slow light" based optical delay lines and atomic memories [4–7] has driven the interest in having narrowband non-classical light sources tuned near an atomic resonance [8, 9]. Four-wave mixing in atomic vapors is a natural choice for producing such light. In addition, proposals for using non-classical light to manipulate cold atoms have been put forth [10, 11] which also require narrowband light near atomic resonance.

We have recently shown that, with the proper choice of operating parameters, non-degenerate, off-resonant 4WM on the D1 line of [85]Rb closely approximates an ideal double-lambda system [12] and can be used to produce entangled twin beams of light. Intensity-difference measurements on bright twin beams produced this way show a high degree of quantum noise reduction, approaching the best values reported for any kind of quantum noise reduction scheme [13, 14]. In addition we have shown that this 4WM process in a hot vapor cell can be used as the basis for constructing a variety of interesting quantum processing devices: a delay line for a portion of an entangled quantum state [15], a low noise amplifier for quantum states [16], and a device to produce entangled images [17]. This naturally brings up the question of whether other atomic lines, with broadly similar level structures, but differing in detail, might also be useful for such purposes.

In this paper we extend our earlier work on the D1 line of [85]Rb and show that quantum noise reduction can also be obtained at the D2 line in [85]Rb as well as at the D1 and D2 lines in

[87]Rb. Under the circumstances we have investigated, the D2 lines appear a less favorable choice than the D1 lines, showing evidence of competing effects beyond 4WM. Still, the levels of quantum noise reduction using the D2 lines are comparable to the levels achieved with other atom-based noise reduction schemes [2, 18]. The results for the D1 line of [87]Rb are complicated by residual [85]Rb in the cell, which produces extra absorption for one of the light beams. Even with this extra absorption, the present [87]Rb cell can be used to produce high levels of quantum correlations. These results strongly suggest that the same method for generating nonclassical light, namely off-resonant, non-degenerate 4WM in a double-lambda system, will be useful in other systems with similar level structures.

2. Experiment

In the present experiments we use 4WM in a hot rubidium vapor to produce bright twin beams of light, called the probe and conjugate, and measure the degree of intensity correlation between them. Such measurements are an experimentally convenient way of characterizing the degree to which the system approximates an ideal 4WM system, free from competing processes. This twin beam source can also be viewed as a linear phase insensitive amplifier [16], the theory of which is well established [19]. Ideally the system is described by a single parameter, the gain G. The input probe beam (power P_{in}) is amplified to produce an output probe beam with power $G P_{in}$ while the output conjugate beam (seeded only by vacuum in our experiment) has power $(G-1)P_{in}$. The noise on the intensity difference between the probe and conjugate beams, expressed in dB relative to the standard quantum limit (SQL), is $-10\log_{10}(2G-1)$ (in the experiment we measure the noise on the power difference between the probe and conjugate beams, but the convention is to refer to this as "intensity difference" since intensity is the quantity calculated in an infinite plane wave model). Here the SQL is defined as the intensity-difference noise on a pair of equal power beams, produced from a coherent laser beam by a beamsplitter, having the same total power as the probe plus conjugate beams. In this paper the term "squeezing" refers to intensity-difference noise levels below the SQL for a pair of twin beams.
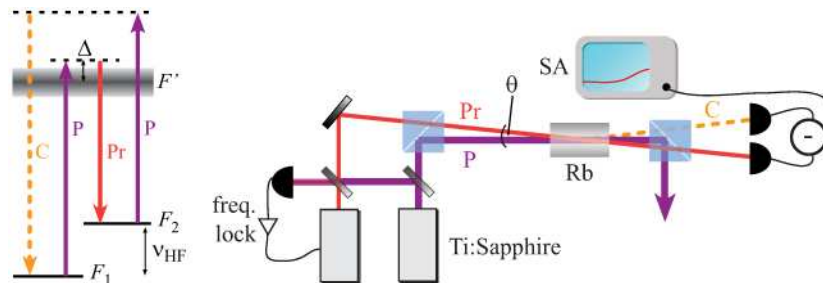

Fig. 1. Left: Energy level diagram showing the double-lambda system. Δ: pump detuning from resonance; v_{HF}: hyperfine splitting in the ground state. Right: Experimental setup. SA: spectrum analyzer; Pr: probe; P: pump; C: conjugate.

To produce the twin beams, a strong pump beam and weak probe beam are overlapped in a vapor cell. Figure 1 (left panel) shows a simplified atomic energy level diagram and the optical fields that make up the double-lambda system. Since one cycle of the 4WM process absorbs two pump photons and produces one probe and one conjugate photon, the intensities of the output probe and conjugate beams are highly correlated. The two lower levels, F_1 and F_2, are the two hyperfine levels in the ground $5S_{1/2}$ state; the upper broadened level is the $5P_{1/2}$ or $5P_{3/2}$ state. The broadening is meant to suggest the presence of several hyperfine levels as well as Doppler broadening of the transition. With this configuration the pump, probe and conjugate fields build coherence between the two atomic ground states, which enhances the efficiency of the 4WM process [20–23].

Figure 1 (right panel) shows the experimental setup. The pump (P) and probe (Pr) beams have orthogonal linear polarizations and are combined on a polarizing beam splitter. The weak probe beam crosses the strong pump beam at a small angle θ (<1°) in a 12 mm long glass cell containing Rb vapor at ≈110 °C. The output probe and conjugate beams are separated from the pump using a polarizing beam splitter and sent to a balanced photodetector. The difference of the two photodiode signals is sent to a radio frequency (RF) spectrum analyzer which displays the noise power in a fixed bandwidth as a function of frequency. All of the noise measurements in this paper were taken at an analysis frequency of 1 MHz. The measured noise signal from the 4WM process is compared to the SQL, established experimentally as described above. Electronics noise and the noise due to scattered pump light have been subtracted from the measured noise levels.

Two independent Ti:Sapphire lasers are used to generate the pump and probe beams. The laser producing the pump is locked to an internal temperature-stabilized reference cavity. The beat note between the two lasers is detected with a high-speed photodiode and is sent to a microwave Mach-Zehnder interferometer. The interferometer consists of an input power splitter, two arms, one with a variable phase delay, and an output mixer. The DC signal from the output mixer is fed to a proportional-integral controller driving the external tuning input of the Ti:Sapphire laser used to generate the probe. For efficient 4WM the pump-probe frequency difference is required to be approximately the atomic ground state hyperfine splitting, ν_{HF} (3.036 GHz for ^{85}Rb, 6.835 GHz for ^{87}Rb). Adjustments of the phase delay in the microwave interferometer provide fine-tuning of the two-photon detuning, $\delta = \nu_P - \nu_{Pr} - \nu_{HF}$ where ν_P and ν_{Pr} are the frequencies of the pump and probe, respectively.

This method keeps the laser frequency difference stable within ≈±2 MHz. In order to see if the residual phase and frequency jitter are important limitations on the observable levels of squeezing, we compared data taken using this locking scheme to that taken using phase locked pump and probe beams produced from a single Ti:Sapphire laser by means of a double-passed 1.5 GHz acousto-optic modulator. Given the available modulator, this single laser scheme could only be used for ^{85}Rb where $\nu_{HF} \approx 3$ GHz. The two different laser locking techniques produced essentially the same level of squeezing on the ^{85}Rb D1 line, at least for an analysis frequency of 1 MHz where we were working. For all of the data in this paper we used the two frequency-locked lasers since this method could be used for both ^{85}Rb and ^{87}Rb.

The level of squeezing produced by the 4WM process depends on the choice of operating parameters: the number density of the Rb vapor, the pump power, the detuning Δ of the pump relative to resonance, the two photon detuning δ, and the crossing angle θ. To fully explore the effects of all these parameters is beyond the scope of the present experiment where our goal is to establish whether or not squeezing can be observed for systems other than the D1 line of ^{85}Rb. To that end we have started with parameters previously established to lead to high squeezing levels for the D1 line of ^{85}Rb and then made small adjustments. Thus our results establish squeezing levels which can be obtained in practice, but do not necessarily represent the absolute best possible values which can be obtained by a full optimization of all parameters for each case. In addition to intrinsic effects due to the atomic level structure, the measured squeezing level is also affected by technical limitations in the apparatus such as losses on the vapor cell windows, the efficiency of the photodetectors, and the quality of polarization filtering to remove pump light. These effects are not very sensitive to the precise laser wavelengths and so are effectively constant for the four systems studied here.

With careful optimization we have measured squeezing levels as high as −8.8 dB using the D1 line of ^{85}Rb [12]. At these high squeezing levels, small losses on the cell windows and other optics, and detector inefficiency, play an important role. The photodiodes we are using have a nominal efficiency of 0.94 and, including other optical losses after the atomic vapor, we estimate an actual detection efficiency of 0.90(3) (all uncertainties are 1 standard deviation combined statistical and systematic). Given a detection efficiency of 90%, the measured

squeezing can never be higher than −10 dB, even if the source produces beams that are more highly squeezed.

In comparing the two isotopes, and the two transitions for each isotope, we will principally be concerned with adjusting the laser tunings. Starting with [85]Rb D1 line, the one-photon detuning, Δ, was set to be about 0.8 GHz blue of the indicated transition (see Fig. 1). The two-photon detuning, δ, was adjusted to give 4WM gain. The exact value depends on the pump laser power and detuning due to AC Stark shifts. The highest squeezing does not generally correspond to the laser tunings that give the highest 4WM gain. Small adjustments of Δ and δ were made to find the highest squeezing. Typically the value of δ for the highest squeezing is a few MHz larger than the value for the highest gain. Once the point of highest squeezing was determined, the value of δ was left fixed and Δ was varied. Thus our data represents one cut through a multidimensional parameter space. In switching from [85]Rb to [87]Rb we also changed the pump power and cell temperature, as discussed below.

For each value of Δ we measured the intensity-difference noise relative to the SQL along with the input probe power and the output probe and conjugate powers. Most of our data is not well described by the ideal phase insensitive amplifier model (even after correcting for detector losses). More useful is a slightly expanded model in which we allow for some intrinsic loss in the medium [12]. Under the conditions of our measurements, the conjugate is much farther detuned from the nearest atomic line than the probe ($\nu_{HF} + \Delta + \delta$ vs. Δ). We assume, therefore, that any loss processes, such as one-photon or Raman transitions, act mainly on the probe. Based on this assumption, we model the medium as having a uniformly distributed gain, as being transparent for the conjugate, and as having a uniformly distributed absorption for the probe beam. In practice, for doing numerical calculations, we treat the medium as being composed of a large number of stages (N) of ideal amplifier gain (each with a gain g slightly greater than 1) interspersed with N beamsplitters (each with a transmission t slightly less than 1). Since loss is modeled by beamsplitters which add only vacuum noise, this model represents a minimal extension of the ideal lossless phase insensitive amplifier model. Given values of g and t the model calculates the power ratios (probe out)/(probe in) and (conjugate out)/(probe in) and the intensity-difference squeezing. To determine g and t we adjust their values until the model reproduces the two measured power ratios. Since there are two adjustable parameters, we can always find values that simultaneously reproduce both measured ratios. Given that the choice of N is arbitrary (as long as it is large), we report below the total inferred gain, $G=g^N$, and the total inferred probe transmission, $T=t^N$, of the entire system, rather than g and t themselves. Determining g and t (done from the power measurements alone) also determines the expected level of intensity-difference squeezing. After adjusting the predicted level of intensity-difference squeezing for detection efficiency we can compare it to the experimentally measured value. More detail can be found in [12].

We now present a summary of the noise reduction levels observed when using the D1 (795 nm) and D2 (780 nm) lines of both Rb isotopes.

3. Observed quantum noise reduction

3.1 [85]Rb D1 line

Figure 2 (left panel, circles) shows the squeezing as a function of pump detuning Δ for a fixed two-photon detuning δ, pump power, cell temperature and crossing angle using the D1 line of [85]Rb. A more extensive discussion of the intensity-difference noise reduction using this line can be found in [12]. The optimal noise reduction in this data set, −8.0(2) dB, was observed for Δ=0.8 GHz. As noted earlier, at high levels of noise reduction the measured value is quite sensitive to small losses and hence small changes in the experimental setup. For [85]Rb, the excited state hyperfine structure is not resolved and thus Δ is measured from the peak of the Doppler broadened line originating on the $F_1 = 2$ ground state level (see Fig. 1). The optimal pump power is a function of other parameters. Depending on the detuning Δ self-focusing/defocusing effects in the non-linear medium can become important. We found

empirically that 400 mW, with a waist of 550 μm ($1/e^2$ intensity radius) in the cell, worked well.
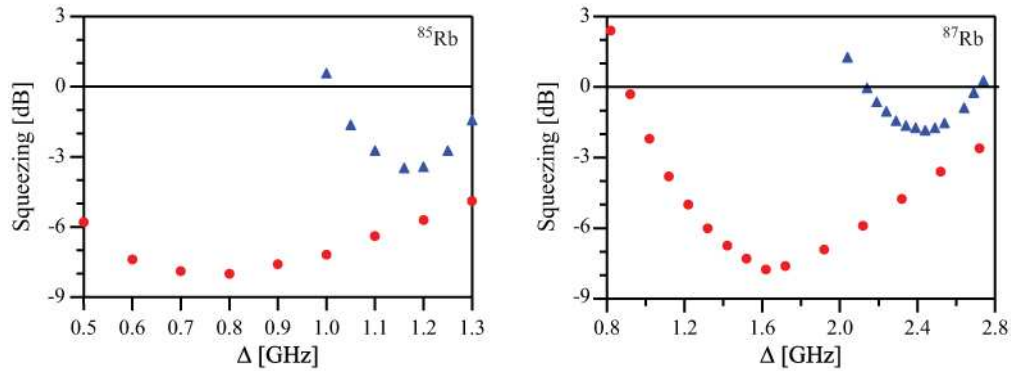

Fig. 2. Observed squeezing levels for the D1 (circles) and D2 (triangles) lines in ^{85}Rb and ^{87}Rb as a function of pump detuning. The two-photon detuning, δ, was held fixed in each of the four scans. For ^{85}Rb the pump power was 400 mW; for ^{87}Rb 700 mW.

Figure 3 shows the gain and probe transmission (expressed in dB's) inferred from the measured probe and conjugate powers using the extension of the ideal amplifier model discussed in the text. Also shown (grey shaded region) are the expected squeezing levels calculated from those gain and probe transmission values, accounting for the final detection efficiency. Over most of the tuning range, the observed squeezing levels for the ^{85}Rb D1 line agree well with the levels predicted from the gain and transmission inferred from the probe and conjugate powers.

3.2 ^{85}Rb D2 line

As shown in Fig. 2, data taken using the D2 line of ^{85}Rb also shows quantum noise reduction below the SQL. Although the level of noise reduction is not as impressive as that observed using the D1 line, the levels seen here are comparable to the best levels of quantum noise reduction observed in other atomic 4WM experiments. The best squeezing is observed for a pump detuning ≈ 1.5 times larger than that for the D1 line.

The curves in Fig. 3 for the D2 line show some important differences from those for the D1 line. The observed probe and conjugate powers, when analyzed through the model, result in a low inferred probe transmission even for large detunings. Most tellingly, the squeezing levels calculated from the model are significantly higher than those actually observed, strongly suggesting the existence of an additional noise mechanism beyond those included in the model. Unlike the case of the ^{85}Rb D1 line, the observed probe and conjugate powers cannot be reconciled with the observed squeezing levels simply by invoking loss on the probe. The numerical values of the gain and transmission calculated from the model thus cannot be considered reliable; the value of the model is to show that there is a qualitative difference between the D2 and D1 lines.

3.3 ^{87}Rb D1 line

In ^{87}Rb, the hyperfine splitting in the ground state is larger (v_{HF} = 6.8 GHz) than in ^{85}Rb (v_{HF} = 3.0 GHz). This increase in v_{HF} leads to a larger detuning from resonance for the lambda system composed of one conjugate photon and one pump photon (Fig. 1). Given the larger detuning, we expect a smaller nonlinear susceptibility relative to ^{85}Rb for the same pump power [22]. In order to raise the gain we increased the pump power from 400 mW (used for ^{85}Rb) to 700 mW, the maximum power available, and also raised the cell temperature. Under these conditions we measure a gain [simple (probe power out)/(probe power in), not the gain inferred from the model] of ≈ 5 for ^{85}Rb, and ≈ 4 for ^{87}Rb when the laser tunings are optimized for the best noise reduction in each case. In ^{87}Rb the excited state hyperfine

structure is partially resolved and thus Δ is measured from the peak of the Doppler broadened $F_1 = 1 \rightarrow F' = 2$ transition. We observe a maximum squeezing level of $-7.8(2)$ dB for $\Delta = 1.6$ GHz.
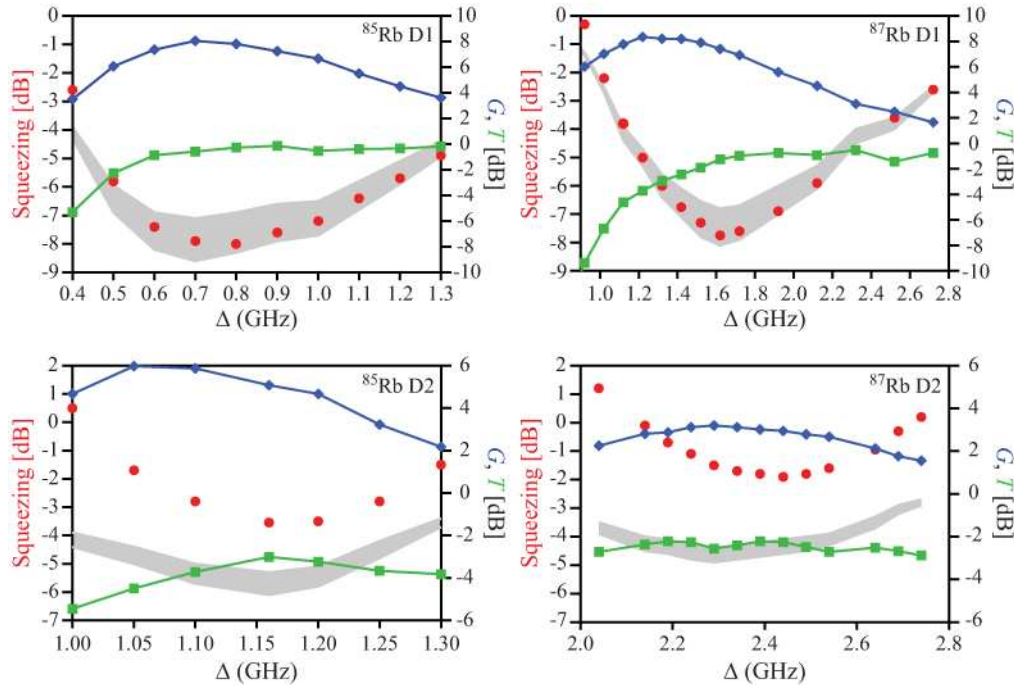

Fig. 3. The gain (G; blue diamonds) and probe transmission (T; green squares) inferred from the measured probe and conjugate powers using the extended ideal amplifier model, along with the measured squeezing (red dots), which was previously shown in Fig. 2. The grey band is the calculated squeezing from the model assuming a detection efficiency of 0.90(3). The width of the band reflects the uncertainty in the detection efficiency. That the model does not work well for either of the D2 lines shows that, in addition to 4WM, there are other processes operating which add noise.

The inferred probe transmission curve seen here (Fig. 3) is similar in shape to that observed for the D1 line of ^{85}Rb but the value of Δ where the probe transmission becomes high is significantly larger for ^{87}Rb than ^{85}Rb, even though the Doppler widths of the ^{87}Rb and ^{85}Rb lines are nearly identical. This increased absorption at small Δ turns out to have a technical origin: although the Rb cell nominally contains only ^{87}Rb, there is a few percent of residual ^{85}Rb present. The relative positions of the absorption lines are such that the ^{85}Rb introduces extra absorption for the probe. Figure 4 shows the probe transmission as a function of frequency. The 4WM gain feature occurs in a spectral region where there is significant absorption by ^{85}Rb. As the pump is tuned further blue, the 4WM feature also moves blue, i.e. away from the ^{85}Rb absorption. Presumably the need to move the 4WM peak away from the ^{85}Rb absorption is the main reason that the optimum squeezing here requires a significantly larger Δ than in ^{85}Rb. If a pure ^{87}Rb cell were available, the optimum squeezing level could be obtained for a smaller Δ with reduced pump power. While it would obviously be advantageous to work with a higher purity sample, even with the level of ^{85}Rb contamination found in our current cell one can select laser parameters which produce high levels of quantum noise reduction.

Despite the extra complication of contamination by ^{85}Rb, the data in the region of good squeezing is well described by the model. Although we have changed parameters to adjust the gain, we see no evidence of a qualitative difference between the ^{85}Rb and ^{87}Rb D1 lines.
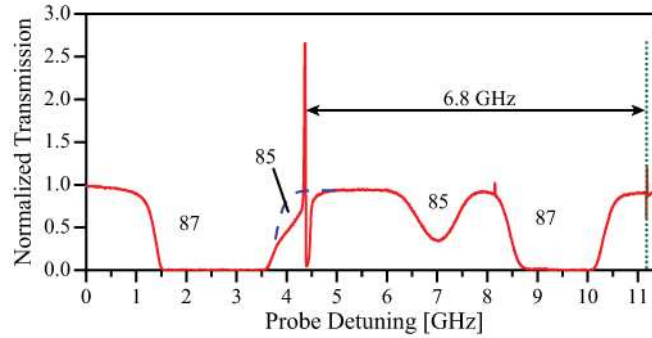
Fig. 4. Transmission spectrum of the probe at the D1 line in [87]Rb as a function of frequency. The absorption dips of [87]Rb and [85]Rb are labeled. The pump frequency is held constant, marked by the dotted (green) line. When the pump and probe frequency difference is ≈ 6.8 GHz, 4WM gain is observed. The dashed (blue) curve shows a curve fit of the [87]Rb absorption dip in the absence of [85]Rb. It shows, qualitatively, that the absorption of the probe is mostly due to residual [85]Rb in the vapor cell. For this scan the cell temperature was raised to ≈ 130 °C.

3.4 [87]Rb D2 line

Although we observe squeezing at the [87]Rb D2 line, the noise reduction is the lowest of the four studied cases. As was seen with [85]Rb, the D2 line requires a larger detuning than the D1 line. As for [85]Rb D2, the probe absorption inferred from the model is significant even at these large detunings. Again, the squeezing levels predicted by the model are significantly higher than the observed levels, signaling that an additional noise mechanism is at work.

4. Discussion

Although we have discussed the 4WM process in terms of a few atomic levels, the real atoms have, of course, more complex structure with multiple hyperfine levels within the excited state and many magnetic sub-levels for each hyperfine line as shown in Fig. 5. Our data show that the two D1 lines behave similarly, as do the two D2 lines, but there is an important difference between the D1 and D2 lines. The fact that [85]Rb and [87]Rb differ in nuclear spin and magnetic moment, and hence in F values and hyperfine splittings, does not appear to be as important as the difference in level structure between the D1 and D2 lines. A full understanding of all of the factors affecting the degree of squeezing observed for each system would require a very detailed model. Absent such a model, we can look to the literature on related non-linear effects to identify differences between the systems that are likely to be important.

Stähler, *et al.* [24] investigated coherent population trapping (CPT) using the D1 and D2 transitions in [85]Rb and concluded that the D1 line provides a higher contrast CPT signal than the D2 line. CPT, like efficient 4WM, requires establishing ground state coherences. Building on the work of previous authors, Stähler, *et al.* noted two important differences between the D1 and D2 lines. The first is that in the D1 line both excited levels $F' = 2, 3$ are coupled to both ground states (see Fig. 5) whereas in the D2 line two of the excited levels $F' = 1, 4$ are each coupled to only one of the two ground state levels. Transitions to $F' = 1, 4$ thus represent a loss mechanism from the desired CPT coherence preparation process. Likewise, in the present experiment, transitions to these levels represent a loss mechanism from the desired parametric 4WM process at small Δ (for which the 4WM peak is within the Doppler profile). This is consistent with our observation that the values of Δ required to see squeezing on the D2 line are larger than those for the D1 line (Fig. 2).
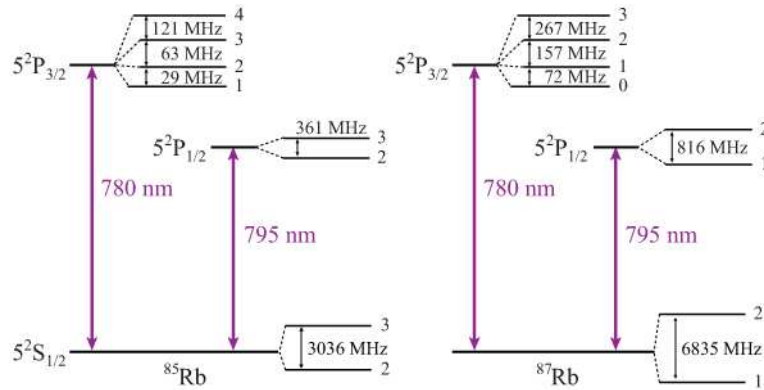
Fig. 5. The hyperfine levels in the [85]Rb (left) and [87]Rb (right) involved in the D1 and D2 transitions, labeled with their F values. From [25].

The second important difference (noted also in [26]) is that the Clebsch-Gordon coefficients in the D1 line are such that it supports simultaneous CPT dark states for transitions involving both excited state hyperfine levels. This is not true for the D2 line and thus one expects, in general, that it is easier to build up ground state coherences using the D1 rather than the D2 line. The ground state coherence enhances the nonlinear gain, and hence we expect to see a larger nonlinear gain in the D1 case. These two effects are consistent with our observation that the D1 line is better than the D2 line for the generation of twin beams.

While these considerations might suggest that the D1 line is a better choice for any type of non-linear process, it is worth noting that Novikova, *et al.* [27] have found that the D2 line provides a better three photon absorption "N-resonance" signal [28] than the D1 line.

5. Conclusion

In this paper we have demonstrated quantum noise reduction measurements for both [85]Rb and [87]Rb using both the D1 and D2 transition lines. With some adjustments in parameters the same basic laser tuning scheme works for all four systems. The optimum choice of pump laser tuning is a balance between the need to tune close to the atomic line in order to have gain and the need to tune away from the line to reduce probe losses. A minimal extension of the ideal amplifier model, allowing for imperfect transmission of the probe beam in the gain medium, shows good agreement with the observations for the D1 lines but not for the D2 lines, pointing to an additional source of noise for the D2 lines. Despite competing effects, there is a range of parameters over which each system approximates, to a greater or lesser degree, an ideal double-lambda 4WM system. We believe that these results are general enough to suggest that applying the same methodology to other systems with similar level structure would result in quantum noise reduction as well.

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