High-contrast coherent population trapping resonances using four-wave mixing in ^{87}Rb

V. Shah, S. Knappe, L. Hollberg, and J. Kitching

Time and Frequency Division, National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

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We demonstrate very high-contrast coherent population trapping[1] (CPT) resonances by using four-wave mixing in ^{87}Rb atoms. In the experiment, we take advantage of the spectral overlap between $F=2\rightarrow F'$ and $F=3\rightarrow F'$ optical resonances on the $D1$ line of ^{87}Rb and ^{85}Rb atoms, respectively, to eliminate the DC-light background from the CPT resonance signal. We observe a CPT resonance with a contrast in the range of 90%, compared with a few percent achieved by alternative methods.

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Recent progress in the development of miniature atomic devices based on coherent population trapping (CPT) such as atomic clocks[2,3] has generated a significant interest in ways to further improve the quality of the detected resonance signal.

A conventional CPT resonance is detected by monitoring the optical power of the bichromatic excitation field absorbed or transmitted by the atoms as a function of the frequency difference between the two fields. One of the drawbacks of using the same light field for both the excitation and the detection of the resonance is that the transmission contrast of the observed signal is typically low, in the best cases approaching 25%,[4] but it can be as low as 0.1%. A low contrast means that the detected DC light power is large compared with the change in power due to the CPT effect.

Most noise processes that contaminate the CPT signal scale with the DC light power. Excess AM noise on the laser, as well as FM noise converted into AM noise by the atomic absorption profile (FM–AM conversion noise[5]), scales proportionally with the DC power. Even the root-mean-square (rms) amplitude of the shot noise is proportional to the square root of the DC power. Here we demonstrate a simple experiment based on four-wave mixing that can almost completely eliminate the DC light background from the CPT resonance signal and therefore allow improved detection resolution.

It has been shown previously[6] that the polarization grating formed in an atomic vapor as a result of CPT can be used for optical phase conjugation through four-wave mixing. In Ref. 6 the phase-conjugate field was generated in a unique spatial mode and separated from the other optical fields by spatial filtering. We show here that a similar four-wave mixing process can be generated by using a single spatial mode and that the conjugate field can be separated from the other fields via polarization and spectral filtering. This optical configuration allows the detection of the CPT resonance with extremely high transmission contrast by using an optical arrangement that is simple and that could be easily miniaturized. The generation of an additional light field in a single spatial mode has been previously demonstrated, for example, by using stimulated Raman scattering,[7] and has been used in atomic clock applications.[8,9] We also note that there are alternative techniques, such as those based on broadband light fields, in which very high contrast resonances can be observed.[10] In these experiments, however, high-intensity light fields were used, which may not be suitable for application in miniature devices.

Two overlapping laser beams are used in this scheme, with orthogonal circular polarizations as shown in Fig. 1. The first beam, denoted Beam-1, is a bichromatic laser field generated by a modulated diode laser in a single spatial and polarization mode. This beam is used to excite a CPT resonance. The second beam, denoted Beam-2 and generated by using a second laser, is a monochromatic field and is used to probe the coherence generated in atomic medium by Beam-1. Through the four-wave mixing process mediated by the atomic vapor, a phase-conjugate field is generated in the same spatial and polarization mode as Beam-2 but is shifted in frequency by an amount equal to the ground state hyperfine splitting frequency. The basic idea here is to observe the conjugate light field only, independent of the background light from other field components, which are eliminated through polarization and spectral filtering.

The experimental setup that was used here is shown in Fig. 2(a). The linearly polarized pump laser

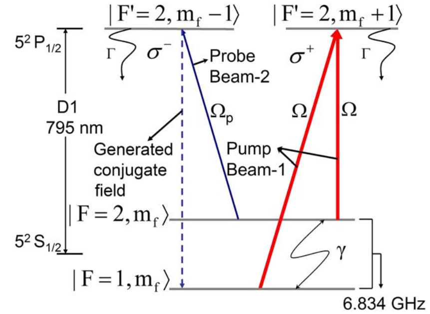

Fig. 1. (Color online) Level scheme used to generate a conjugate field using four-wave mixing in a double-Λ system in ^{87}Rb. Here Ω and Ω_p are the Rabi frequencies due to light fields connecting the ground states and the excited states. For simplicity it is assumed that the excited states decay to the ground states with an equal decay rate given by Γ and that the ground state population and coherence decay at a rate given by γ.

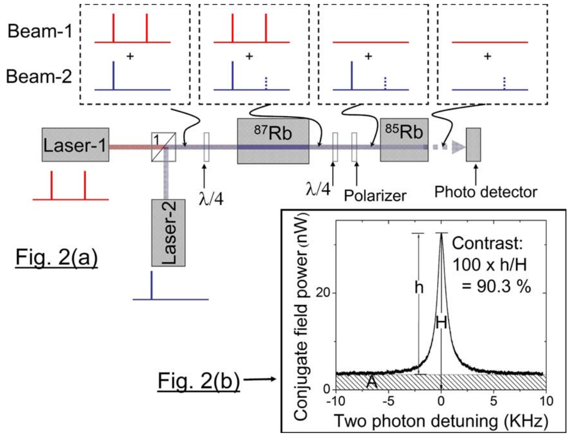

Fig. 2. (Color online) (a) Experimental setup used to observe the conjugate light field against a nearly zero light background. 1, Polarizing beam splitter. (b) Conjugate light field power detected as a function of detuning from the two-photon resonance (from 6.83468 GHz). A, Light background due to a secondary laser mode.

field, Beam-1, is circularly polarized (say σ^+) by the use of a quarter-wave plate and is tuned to the $D1$ transition in ^{87}Rb at 795 nm. The lasers used in this experiment were low-power vertical cavity surface emitting lasers. The laser injection current is modulated at 3.417 GHz to generate two first-order sidebands that excite a CPT resonance on the atomic hyperfine ground states.[11] A second probe laser beam, Beam-2, is combined with Beam-1 by using a polarizing beam splitter and is also circularly polarized after passing through the quarter-wave plate (with orthogonal polarization with respect to Beam-1). Beam-2 is tuned to the $F=2 \rightarrow F'$ transition on the $D1$ line in ^{87}Rb atoms. The interaction between the probe laser beam and the coherently excited ^{87}Rb atoms spontaneously generates an additional, conjugate light field through the nonlinear process of four-wave mixing.[6,12] The conjugate light field has the same polarization and propagates in the same direction as the probe laser.

After the light fields pass through the ^{87}Rb vapor cell, Beam-1 is eliminated by using a quarter-wave plate and a polarizer arrangement. Beam-2 and the generated conjugate field then enter an optically dense ^{85}Rb vapor cell. This cell appears opaque to Beam-2 while allowing the conjugate light field to pass through largely unattenuated (less than 5% attenuation). The use of a ^{85}Rb filter cell is fairly common in applications such as conventional lamp-based optically pumped atomic clocks, where it is used to eliminate the spectral frequency components that can excite the $F=2$ hyperfine ground state in ^{87}Rb atoms. The use of a ^{85}Rb vapor cell in a manner similar to our use was demonstrated earlier in Ref. 13. The conjugate light field, which is generated only when the two-photon resonance condition is satisfied by the pump fields, is then detected against a nearly zero light background by using a Si p-i-n photodetector.

Figure 2(b) shows a typical resonance signal. The estimated peak intensity of Beam-1 in this case was 6.2 mW/cm^2 and that of Beam-2 was 1.16 mW/cm^2. The full width at half-maximum (FWHM) of Beam-2 was equal to 0.09 cm. The ^{87}Rb vapor cell used in the experiment had a volume of $1 \times 1 \times 4.5$ cm^3 and contained a mixture of nitrogen and argon buffer gases at a total pressure of 6.6 kPa. The temperature of the vapor cell was stabilized such that the optical absorption was near 96%. The vapor cell was enclosed inside a two-layer magnetic shield such that the Zeeman sublevels on the hyperfine ground state were degenerate. Resonances with equally high contrast (but smaller magnitude) were also observed between individual Zeeman sublevels when a small longitudinal magnetic field was applied to lift their degeneracy. In the experiment, the conjugate light field was detected with a contrast in the range of 90%. The main limitation to achieving even higher contrast was the presence of an additional spectral mode in Beam-2 that was detuned from the primary mode by roughly 2 GHz. Additional but suppressed spectral modes are common in most types of laser, often as a result of spectral hole burning in the gain medium. Because of the detuning of this additional mode, the power in this mode was not absorbed by atoms in the ^{85}Rb cell and was therefore detected by the photodiode. The contrast observed in the conventional case by using a single laser (Beam-1) was about 16% with a resonance amplitude of 0.76 μW under optimal conditions. The FWHM of Beam-1 was equal to 0.11 cm.

Figure 3(a) shows the power of the generated conjugate light field as a function of the intensity of Beam-2 for various values of the intensity of Beam-1. It was found that when both the pump and the probe intensities were relatively high, the strength of the conjugate light field saturated, and a further increase in the Beam-2 intensity actually decreased the strength of the conjugate field. This behavior is consistent with the observations made in Ref. 12 and can be intuitively understood in the following way. The strength of the conjugate light field is directly proportional to the coherence generated in the media. This coherence saturates as a function of intensity of Beam-1, and very high Beam-2 intensities destroy the coherence generated in the medium by pumping

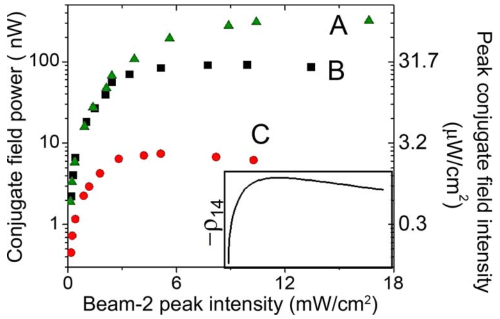

Fig. 3. (Color online) (a) Power of the generated conjugate light field at zero two-photon detuning as a function of Beam-2 intensity for different Beam-1 intensities. The peak pump intensities were A, 13.6; B, 6.2; C, 1.62 mW/cm^2. The pump and the probe powers were measured at the entrance of the ^{87}Rb vapor cell. Inset, coherence element, ρ_{14}, at $\delta=0$ as a function of the probe optical pumping rate, T; $\Upsilon=1.25\gamma$, $\Gamma=100\gamma$, and T was varied from 0 to 8γ. The scale on the y axis ranged from 0 to 0.05.

atoms out of the coherent dark state. This qualitative behavior can also be reproduced theoretically by using density matrix analysis of the four-level atom model shown in Fig. 1. The coherence element, ρ_{14}, between the energy levels in which the conjugate field is generated has a negative value. This is responsible for the spontaneous generation of the conjugate field and is given by

$$\rho_{14} = \frac{1}{\sqrt{\Gamma}} \frac{\sqrt{2}\sqrt{T}\Upsilon(\gamma + T + 2\Upsilon)}{\delta^2 + (\gamma + T + 2\Upsilon)^2}, \tag{1}$$

where Υ and T are the optical pumping rates defined as $\Omega^2/2\Gamma$ and $\Omega_p^2/2\Gamma$, respectively, and δ is the two-photon detuning. The following assumptions were made in these calculations, which are similar to ones made in Ref. 14. Equation (1) was derived under the steady-state condition, and it was assumed that $\Gamma \gg \delta, \gamma, \Upsilon$ T. It was also assumed that the single photon detuning of the probe field was equal to zero, and that of the pump fields, δ_1 and δ_2, was such that $\delta_1 = -\delta_2 = \delta/2$. The experimentally observed behavior of the conjugate field as a function of the intensities of Beam-2 and the Beam-1 is consistent with the behavior seen in Eq. (1) [Fig. 3(b)]. The linewidth of the conjugate field as a function of the two-photon resonance was also found to be in qualitative agreement with the expression $(\gamma + T + 2\Upsilon)$, shown in Eq. (1). We note, however, that a more thorough analysis would account for effects such as the optical thickness of the atomic medium and presence of higher-order sidebands, which is not done here.

To evaluate the improvement in the performance of atomic clocks or magnetometers using this technique, it is necessary to carefully weigh the benefits of high resonance contrast over the loss in signal strength due to finite conversion efficiency of the four-wave mixing process. Under optimal conditions, the average power generated in the conjugate field was about 12% of the change in power associated with the conventional CPT resonance measured with Beam-1. At the same time, the conjugate signal was detected with a roughly six times higher contrast. The resonance linewidths in both cases were nearly equal. The resulting change in the performance is therefore expected to be small if the system is photon shot-noise limited. Under different experimental conditions, however, such as those for which the CPT contrast in the conventional case is not as high, the relative advantage in using this technique can be much more significant. These conditions may occur, for example, in a vapor cell with relatively high buffer gas pressure or when operating at lower optical intensities. Also, in most cases the traditional CPT signal-to-noise ratio is limited by the excess laser noise contribution from the DC light background, which is essentially eliminated by using the current approach.

We have demonstrated very high-contrast CPT resonances using four-wave mixing. In the experiment, around 90% contrast was seen by the use of a simple and inexpensive system based on vertical cavity surface emitting lasers. The observed experimental results were analyzed using a simple density matrix formalism and found to be in good qualitative agreement. The contrast seen in the experiment was limited mainly by the presence of a secondary spectral mode in the laser. Even though the strength of the generated conjugate light field depends on the intensity of the incident fields, a high contrast can be achieved in this system even at very low intensities of the incident light fields (assuming that the residual optical power in secondary spectral modes of the probe field remains a small fraction of the power probe field). Also, since the conjugate light field, which is detected independently of the background light, is strongly related to the coherence properties of the atomic media, this technique may provide a simple and powerful tool for investigation in areas such as slow light, using electromagnetically induced transparency and quantum memory applications.[13]

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References

1. G. Alzetta, A. Gozzini, L. Moi, and G. Orriols, Nuovo Cimento Soc. Ital. Fis., B **36**, 5 (1976).
2. J. Vanier, A. Godone, and F. Levi, Phys. Rev. A **58**, 2345 (1998).
3. S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L. A. Liew, and J. Moreland, Appl. Phys. Lett. **85**, 1460 (2004).
4. M. Zhu, in *2003 IEEE International Frequency Control Symposium* (IEEE, 2003), p. 16.
5. J. G. Coffer, M. Anderson, and J. C. Camparo, Phys. Rev. A **65**, 033807 (2002).
6. P. R. Hemmer, D. P. Katz, J. Donoghue, M. Cronin-Golomb, M. S. Shahriar, and P. Kumar, Opt. Lett. **20**, 982 (1995).
7. M. D. Lukin, M. Fleischhauer, A. S. Zibrov, H. G. Robinson, V. L. Velichansky, L. Hollberg, and M. O. Scully, Phys. Rev. Lett. **79**, 2959 (1997).
8. N. Vukicevic, A. Zibrov, L. Hollberg, F. Walls, J. Kitching, and H. Robinson, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **47**, 1122 (2000).
9. A. S. Zibrov, H. G. Robinson, V. L. Velichansky, V. V. Vasiliev, L. Hollberg, E. Arimando, M. D. Lukin, and M. O. Scully, in *5th Symposium on Frequency Standards and Metrology*, J. C. Bergquist, ed. (World Scientific, 1996), pp. 490–492.
10. G. Alzetta, S. Gozzini, A. Lucchesini, S. Cartaleva, T. Karaulanov, C. Marinelli, and L. Moi, Phys. Rev. A **69**, 063815 (2004).
11. N. Cyr, M. Tetu, and M. Breton, IEEE Trans. Instrum. Meas. **42**, 640 (1993).
12. B. Lu, W. H. Burkett, and M. Xiao, Opt. Lett. **23**, 804 (1998).
13. M. D. Eisaman, L. Childress, A. André, F. Massou, A. S. Zibrov, and M. D. Lukin, Phys. Rev. Lett. **93**, 233602 (2004).
14. J. Vanier, M. W. Levine, D. Janssen, and M. Delaney, Phys. Rev. A **67**, 1065801 (2003).