Generation of coherent population trapping resonances with nearly 100% transmission contrast

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***Abstract*— We demonstrate a simple setup for observing very high contrast coherent population trapping resonances in rubidium-87. The high contrast is achieved by eliminating the DC-light background through polarization and spectral filtering.**

I. Introduction

Recent progress in the field of atomic devices based on coherent population trapping (CPT) [1]–[3] such as atomic clocks [4]–[6] and magnetometers [7]–[9] has generated a significant interest in ways to further improve the quality of the detected resonance signal. Several different advances have been demonstrated with encouraging results, such as reducing the CPT resonance linewidth [10], [11], increasing the resonance amplitude [11]–[14] and reducing the laser FM-AM noise [15]. These results are generally expected to improve the frequency stability in the case of atomic clocks or improve the sensitivity to magnetic fields, in the case of magnetometers.

A conventional CPT resonance is detected by monitoring absorbtion of a bichromatic optical excitation field by alkali atoms. Depending on the details of the experiment, the CPT resonance contrast[1] varies from below 0.1% to a maximum approaching 25% [16]. Because of this low contrast, a majority of the light falling on the photodetector is unwanted DC-light background. This light background not only contributes to the photon shot noise but also to the amplitude and the FM-AM conversion noise [17] which scales linearly with optical power. Here we demonstrate a simple experiment based on four-wave mixing that can almost entirely eliminate the DC light background from the CPT resonance signal and therefore allow improved detection resolution.

The basic idea behind this technique is to use four-wave-mixing in atomic vapor to generate a conjugate light field [18]. The conjugate field is generated only when the two-photon resonance condition is satisfied by the bichromatic CPT excitation fields. After the excitation fields pass through the atomic vapor, they are eliminated by polarization and spectral filtering using a rubidium-85 filter cell. This allows the detection of the generated conjugate field against nearly zero optical background.

[1]Contrast is defined as 100 × ratio of CPT resonance amplitude to the total light background on resonance.

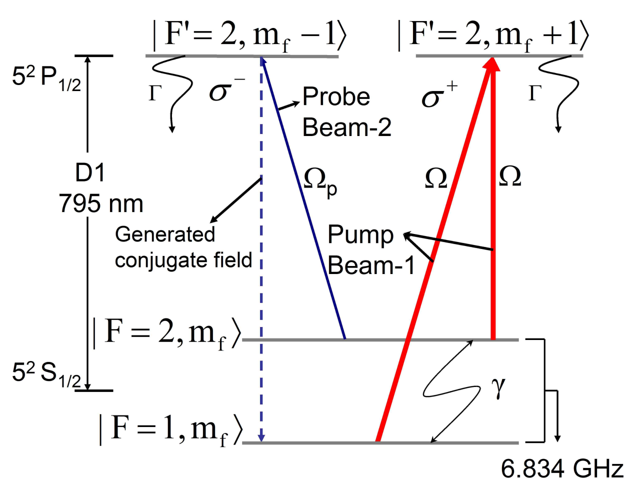

Fig. 1. Level scheme used to generate a conjugate field using four wave mixing in a double Λ system in ^{87}Rb. Here, Ω and Ω_p are the Rabi frequencies connecting the ground states and the excited states. For simplicity it is assumed that the excited states decay to the ground states with an equal decay rate given by Γ and the ground state population and coherence decay at a rate given by γ. A phase conjugate light filed is generated between energy levels $|F=1, m_f\rangle$ and $|F'=2, m_f-1\rangle$

II. Theory

The process of four wave mixing in an atomic vapor has been extensively studied, for example, in the context of frequency up or down conversion [19], [20]. The phase conjugate light field that is generated has several interesting properties many of which are particularly useful in the field of quantum optics and quantum communications.

Consider the atom-light system shown in Figure 1. The light fields incident between levels $|F=1, m_f\rangle - |F'=2, m_f+1\rangle$ and $|F=2, m_f\rangle - |F'=2, m_f+1\rangle$ are coherent and are used to excite a CPT resonance. A light field, Ω_p, with orthogonal polarization resonant between $|F=2, m_f\rangle - |F'=2, m_f-1\rangle$ is used to probe the coherence that is generated in the atomic medium by the CPT light fields. Through a four wave mixing process mediated by the atomic vapor, a phase conjugate field that is shifted in frequency by an amount equal to the ground state splitting frequency is generated [18], [21]. This process can be analyzed using density matrix formalism [22].

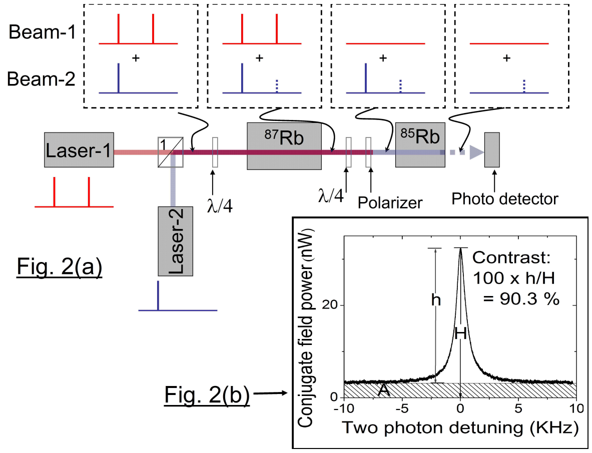

Fig. 2. (a) Experimental setup used to observe the conjugate light field against a nearly zero light background. 1: Polarizing beam splitter. (b) Conjugate light field power detected as a function of detuning from the two-photon resonance (from 6.83468 GHz). A: Light background due to a secondary laser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

Making assumptions similar to those made in Ref. [23], an analytic expression for the atomic density matrix elements can be obtained under steady state conditions. Specifically, the coherence element $Im[\rho_{14}]$, between the energy levels in which the conjugate field is generated is given by

$$Im[\rho_{14}] = -\frac{1}{\sqrt{\Gamma}} \frac{\sqrt{2}\sqrt{T}\Upsilon(\gamma + T + 2\Upsilon)}{\delta^2 + (\gamma + T + 2\Upsilon)^2}, \quad (1)$$

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. It was assumed here 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 spatial absorbtion of a light field, Ω_i, resonant between atomic energy levels i and j is given by [23]

$$\frac{d\Omega_i}{dz} = -\alpha_i \times Im[\rho_{ij}], \quad (2)$$

where α_i is the absorption coefficient defined as,

$$\alpha_i = \left(\frac{\omega_{Li}}{c\epsilon_0\hbar} d_i^2\right) n. \quad (3)$$

In Eq. (3), n is the density of the atoms, ϵ_0 is the permittivity of vacuum, c is the speed of light and $\hbar$ is Plank's constant. The electric dipole moment, d_i, is the component of electric dipole moment along the direction of the traveling co-propagating light fields (z).

From Eq.(2), it can be seen that $Im[\rho_{ij}]$ with a negative value leads to an overall amplification of the light field Ω_i as it propagates through the atomic medium. This is responsible for generation of the conjugate light fields between energy levels $|F = 1, m_f\rangle$ and $|F' = 2, m_f - 1\rangle$.

III. Experiment

The experimental setup that was used here is shown in Figure 2(a) and is described in detail in Ref. [24]. Two linear, orthogonally polarized light fields, Beam-1 and Beam-2, were generated by vertical-cavity-surface-emitting-lasers (VCSEL). Both beams were tuned to the D1 line of rubidium-87 and were combined together in the same spatial mode using a polarizing beam splitter. The two beams were circularly polarized using a quarter wave plate and passed through an enriched rubidium-87 vapor cell containing nitrogen buffer gas.

The pump beam, Beam-1, was a bichromatic field generated by modulating the injection current of the VCSEL at 3.417 GHz and was used to excite a CPT resonance. The second monochromatic beam, Beam-2, was used to the probe the coherence generated in the atomic medium by Beam-1. Through the process of four-wave-mixing in the atomic vapor, a phase conjugate light field was generated in the same spatial and polarization mode as Beam-2 but shifted in frequency by an amount equal to the ground state hyperfine splitting frequency (see Fig. 1).

After passing the light fields through the vapor cell, Beam-1 was eliminated using a quarter waveplate polarizer arrangement and the Beam-2 was eliminated using an optically thick rubidium-85 filter cell. The remaining conjugate field was then detected independent of any light background.

When the two photon CPT resonance condition is not satisfied by the optical fields in Beam-1, the conjugate field is not generated and there is almost complete absence of any light falling on the photodetector. Under realistic experimental conditions, however, there is always some light that leaks onto the photodetector and this is the main factor that determines the CPT resonance contrast when using this technique. This is unlike the conventional case in which the resonance contrast depends on factors such as the intensity of the incident light fields and the buffer gas pressure in the vapor cell [13]. In the experiment, we observed CPT resonances with contrast in the range of 90% (Fig. 2(b)). The contrast seen here was limited by roughly 3 nW of light leaking onto the photodetector. A majority of this leakage light was attributed to a secondary spectral mode in Beam-2 that was detuned from the primary mode by roughly 2 GHz.

IV. Conclusion

We have demonstrated a novel technique for observing CPT resonances with a very high contrast in rubidium-87 atoms. Unlike in the conventional case, the resonance contrast here mainly depends on spectral purity of the laser and the quality of the polarization filtering components. This allows a unique possibility of observing very high resonance contrasts even at very low light intensities and at relatively high buffer gas pressures. In the experiment, a contrast in the range of 90% was seen using simple and inexpensive VCSEL lasers. This contrast was mainly limited by the spectral purity of the laser.

Apart from the utility of this technique in applications such as atomic clocks and magnetometers, this may provide a simple and powerful tool for investigation in areas such as slow light using EIT and quantum memory applications [25].

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REFERENCES

[1] W.E. Bell, A.L. Bloom, "Optically driven spin precession," *Phys. Rev. Lett.*, vol. 6, no. 6, p. 280, March 1961.

[2] G. Alzetta, A. Gozzini, L. Moi, and G. Orriols, *Nuovo Cimento Soc. Ital. Fis. B*, vol. 36, p. 5, 1976.

[3] E. Arimondo, "Coherent population trapping in laser spectroscopy," *Prog. Opt.*, vol. XXXV, p. 257, 1996.

[4] J. Vanier, A. Godone, F. Levi, "Coherent population trapping in cesium: Dark lines and coherent microwave emission," *Phys. Rev. A*, vol. 58, p. 2345, 1998.

[5] S. Knappe, V. Shah , P.D.D. Schwindt, L. Hollberg, J. Kitching, L.A. Liew, J. Moreland, "Microfabricated atomic frequency references." *Appl. Phys. Lett.*, vol. 85, no. 9, pp. 1460–1462, 2004.

[6] R. Lutwak, P. Vlitas, M. Varghes, M. Mescher, D.K. Serkland, G.M. Peake, "The mac - a miniature atomic clock," in *Freq. Cont. Symp.* IEEE, August 2005, pp. 752–757.

[7] M.O. Scully and M. Fleischhauer, *Phys. Rev. Lett.*, vol. 69, p. 13601363, 1992.

[8] A. Nagel, L. Graf, A. Naumov, E. Mariotti, V. Biancalana, D. Meschede and R. Wynands, *Euro. Phys. Lett*, vol. 44, pp. 31–36, 1998.

[9] P. D.D. Schwindt, S. Knappe, V. Shah, L. Hollberg, J. Kitching, L. Liew and J. Moreland, *Appl. Phys. Lett.*, vol. 85, p. 6409, 2004.

[10] Y.-Y. Jau, A. B. Post, N. N. Kuzma, A. M. Braun, M. V. Romalis, W. Happer, "Intense, narrow atomic-clock resonances," *Phys. Rev. Lett.*, vol. 92, p. 110801, 2004.

[11] T. Zanon, S. Guerandel, E. de Clercq, D. Holleville, N. Dimarcq, A. Clairon, "High contrast ramsey fringes with coherent-population-trapping pulses in a double lambda atomic system," *Phys. Rev. Lett.*, vol. 94, p. 193002, 2005.

[12] S.V. Kargapoltsev, J. Kitching, L. Hollberg, A.V. Taichenachev, V.L. Velichansky, V.I. Yudin, "High-contrast dark resonance in sigma(+)-sigma(-) optical field," *Laser Phy. Lett.*, vol. 10, p. 495, 2004.

[13] Y.Y. Jau, E. Miron, A.B. Post, N.N. Kuzma, W. Happer, "Push-pull optical pumping of pure superposition states," *Phys. Rev. Lett.*, vol. 93, no. 16, p. 160802, 2004.

[14] V. Shah, S. Knappe, P. D. D. Schwindt, V. Gerginov, and J. Kitching, "Compact phase delay technique for increasing the amplitude of coherent population trapping resonances in open lambda systems," *Opt. Lett.*, vol. 31, pp. 2335–2337, 2006.

[15] M. Rosenbluh, V. Shah, S. Knappe, and J. Kitching, *Opt. Exp.*, vol. 14, pp. 6588–6594, 2006.

[16] M. Zhu, "High contrast signal in a coherent population trapping based atomic frequency standard application," *IEEE Intl. Freq. Cont. Symp.*, p. 16, May 2003.

[17] J. G. Coffer, M. Anderson, and J. C. Camparo, "Collisional dephasing and the reduction of laser phase-noise to amplitude-noise conversion in a resonant atomic vapor," *Phys. Rev. A*, vol. 65, no. 3, p. 033807, Feb 2002.

[18] P. R. Hemmer, D. P. Katz, J. Donoghue, M. Cronin-Golomb, M. S. Shahriar, P. Kummar, "Efficient low-intensity optical phase conjugation based on coherent population trapping in sodium," *Opt. Lett.*, vol. 20, p. 982, 1995.

[19] S. Babin, U. Hinze, E. Tiemann, B. Wellegehausen, *Opt. Lett*, vol. 21, p. 1186, 1996.

[20] A. J. Merriam, S. J. Sharpe, M. Shverdin, D. Manuszak, G.Y. Yin, and S. E. Harris, *Phys. Rev. Lett*, vol. 84, p. 5308, 2000.

[21] B. Lu, W. H. Burkett, M. Xiao, "Efficient low-intensity optical phase conjugation based on coherent population trapping in sodium," *Opt. Lett.*, vol. 23, pp. 804–806, 1998.

[22] V. Shah, "Microfabricated atomic clocks based on coherent population trapping," Ph.D. dissertation, University of Colorado at Boulder, 2007.

[23] J. Vanier, M. W. Levine, D. Janssen, M. Delaney, *Phys. Rev. A*, vol. 67, p. 069801, 2003.

[24] V. Shah, S. Knappe, L. Hollberg, and J. Kitching, *Opt. Lett*, vol. 32, p. 1244, 2007.

[25] M. D. Eisaman, L. Childress, A. André, F. Massou, A. S. Zibrov, and M. D. Lukin, "Shaping quantum pulses of light via coherent atomic memory," *Phys. Rev. Lett.*, vol. 93, no. 23, p. 233602, Nov 2004.