Coherence induced correlation and anti-correlations

Yanhong Xiao,[1,**], **Tun Wang,**[2,3], **Maria Baryakhtar,**[4],**Michael Crescimanno,**[5], **Michael Hohensee**[1], **David F. Phillips**[1], **Susanne F. Yelin**[2,6], **Ronald L. Walsworth,** [1,4]

[1]*Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, 02138 USA*

[2]*Department of Physics, University of Connecticut,Storrs,CT 06269, USA*

[3]*ITP, Univ. Innsbruck, Switzerland*

[4]*Department of Physics, Harvard University, Cambridge, MA, 02138 USA*

[5]*Department of Physics and Astronomy, Youngstown State University, Youngstown, OH 44555-2001*

[6]*ITAMP, Cambridge, MA,02138 USA*

[**]*Corresponding author: yxiao@cfa.harvard.edu*

Compiled September 16, 2009

Although electromagnetically induced transparency (EIT) is well understood from the steady state evaluation of a simple quantum optics model, noise induced by this two-photon resonance has recently received much recent experimental interest because it is somewhat less well understood and is being evaluated for fundamental metrology. We report on a simple intuitive and quantitative physical picture for the conversion of laser phase noise into intensity noise in EIT. This view relates the observed transition between intensity noise correlation and anticorrelation in terms of the changes in the slope of the one-photon resonances as one detunes through the two photon resonance. This analytic approach quantitatively connects the steady state solution of the quantum optics model with experimental signatures including the power-broadening-free resonance, correlation zeros at detuning equal width and contrast versus overall one-photon detuning.

Noise in the optical response of two- and three- level atomic systems illuminated by lasers has been studied since the late 80's [?, ?, ?]. These studies have sought to characterize the observed changes in the light's intensity noise spectra in terms of fundamental non-linear optical processes [?, ?]. Understanding intensity noise from vapor cells has ramifications for CPT clocks [?], EIT based magnetometers and quantum memory.

Diode lasers have low intensity noise and high phase noise which is associated with a large spectral linewidth typically ranging from tens of kHz to hundreds of MHz. Phase noise converts to intensity noise after near-resonant interaction with an atomic medium. Throughout this note we focus only on multiplicative noise processes and ignore endogenous noise sources from the vapor cell, as experiments indicate that this later source of noise is typically small. Recently experimental studies [?, ?, ?] have revealed new aspects of the noise spectra from EIT prepared media, such as the power-broadening-free resonance in the intensity cross correlation [?, ?], of potential interest in precision spectroscopy and quantum optics metrology.

We consider EIT in a generic three level Λ system composed of two metastable ground states $|a\rangle$, $|b\rangle$ and an excited state $|e\rangle$. For simplicity we assume that two laser fields with the same Rabi frequency $\Omega_a = \Omega_b = \Omega$ are on resonance with transitions $|a\rangle \rightarrow |e\rangle$ and $|b\rangle \rightarrow |e\rangle$ respectively. To further simplify and relate to the light from laser diodes, we assume that there are essentially no intensity fluctuations of these light fields, but that that their frequency varies jointly over a large bandwidth. After the cell the intensities of each light field are separately digitized and crosscorrelated in a spectrum analyzer, giving a signal proportional to $g_2(t) \equiv \frac{\langle \delta I_1(t)\delta I_2(0)\rangle}{\sqrt{\langle(\delta I_1)^2\rangle\langle(\delta I_2)^2\rangle}}$, where $\delta I_{1,2}$ are intensity fluctuations for the two fields. In the optically thin limit in which we also ignore endogenous noise sources in the cell, the intensity noise cross correlator can be written entirely in terms of the variations of the optical susceptibilities,

$$g^2(t) = \frac{\langle Im(\Omega_a \delta\rho_{ea}(t))\, Im(\Omega_b \delta\rho_{eb}(0))\rangle}{\sqrt{\langle(Im(\Omega_a \delta\rho_{ea}))^2\rangle\langle(Im(\Omega_b \delta\rho_{eb}))^2\rangle}} \qquad (1)$$

with $\langle\rangle$ denoting the average over the frequancy excursions, the ρ_{ij} the density matrix.

The offset of the two one-photon resonances is directly related to $g^2(0)$. To illustrate this connection, we assume the laser frequency is locked at a fixed one-photon detuning, for instance $\delta_0 = 0$ (position is indicated by the dashed lines in Fig. **??**). Since the offset is caused by ground state coherence which cannot follow the fast fluctuations of laser phase (hence frequency), the slope relations will remain the same as that shown in Fig. **??** from where we can deduce that $g^2(0) \approx 1$

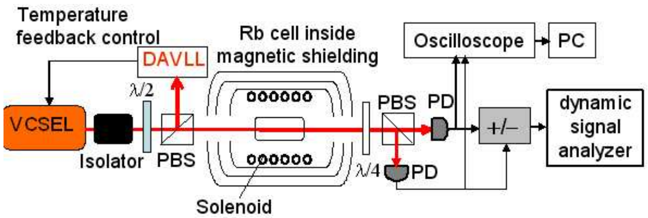

Fig. 1. Schematics of experimental setup for Zeeman EIT.

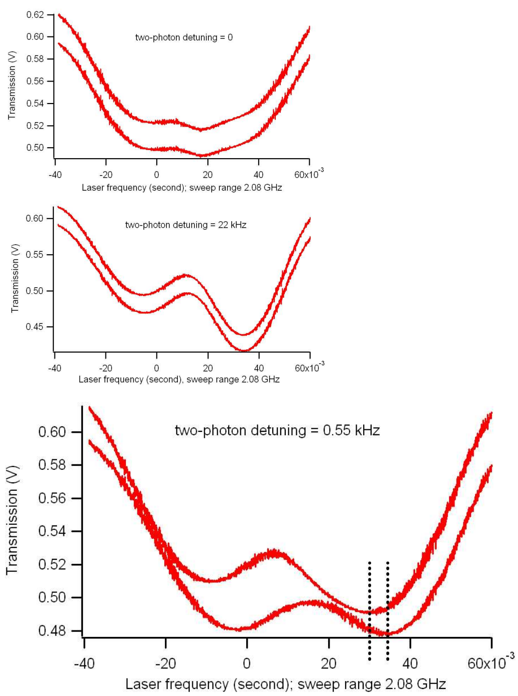

Fig. 2. One-photon transmission spectrums of the two EIT fields for three two-photon detunings. Laser frequency sweeps through transitions $|F=2\rangle \rightarrow |F'=2\rangle$and $|F=2\rangle \rightarrow |F'=1\rangle$, from left to right. Large offset of two spectrums up to 120 MHz appears for $\Delta = 550$Hz. Other parameters: $\Gamma \approx 100$ Hz, laser power 170 μW, beam diameter 3.7 mm, cell with 2 Torr Ne buffer gas.

for zero (Fig. **??**(a))and large Δ (Fig. **??**(b))because the slopes are completely parallel, and ≈ -1 for $\Delta = 550$ Hz because the slopes are completely opposite(Fig. **??**(c)).

We now address at what two-photon detunings transitions between anti-correlation and correlation happen. To simply the analysis, we assume that one-photon detuning is zero (then $d = 0$ in Eq. (**??**)). Using Eq. (**??**), the numerator of the g^2 in Eq. (**??**) can be rewritten as

$$G^2(0) = \langle \delta Im(\rho_{ea}(t)) \delta Im(\rho_{eb}(t)) \rangle \quad (2)$$
$$= 0.25 \left\{ \langle (\delta Im(\rho_{ea} + \rho_{eb}))^2 \rangle - \langle (\delta Im(\rho_{ea} - \rho_{eb}))^2 \rangle \right\}$$
$$= 0.25\Omega((\frac{1}{2} + Re(\rho_{ab}))^2 (\delta \frac{\gamma/2}{(\gamma/2)^2 + \delta_0^2})^2$$
$$- Im^2(\rho_{ab})(\delta \frac{\delta_0}{(\gamma/2)^2 + \delta_0^2})^2)$$

Finally, we remark on the role of two-photon phase noise, which exists if two-independent laser sources are used, or the EIT fields are produced by phase modulating a laser with a RF source which is not phase noise free. In our Zeeman EIT experiment, amplitude noise in the magnetic field can induce effective two-photon phase noise. We have used a stable current source for the magnetic field generation, and checked that the two-photon noise influence is negligible. In cases where it is not negligible, $g^2(0)$ value will be closer to zero for the entire $g^2(0)$ v.s.Δ curve, due to the unsyncronized phase noise itself (reduce correlation) and decreased ground state coherence(reduce anticorrelation).

In conclusion, we demonstrate that EIT ground state coherence can lead to large offset of the otherwise overlapped one-photon transmission spectrums of the two EIT fields. This phenomena is the essence of anticorrelation in the intensity fluctuations in the two EIT fields. Our physics picture provides intuition to the noise processes in the system, and is useful for applications.

We are grateful to J. Vanier for bringing our attention to laser phase noise in EIT and to I. Novikova for useful discussions. This work was supported by ONR, DARPA, ITAMP and the Smithsonian Institution.

References

1. K. Rzazewski, B. Stone, and M. Wilkens, "Laser-noise-induced intensity fluctuations in resonance flourescence," *Phys. Rev. A* **40**, 2788-2791 (1989).
2. T. Yabuzaki, T. Mitsui, U. Tanaka, "New type of high-resolution spectroscopy with a diode laser," *Phys. Rev. Lett.* **67**, 2453-2457 (1991).
3. Th. Haslwanter, H. Ritsch, J. Cooper, and P. Zoller, "Lasernoise-induced population fluctuations in two- and threelevel systems," *Phys. Rev. A* **38**, 5652-5659 (1988).
4. B. J. Dalton and P. L. Knight, "The effects of laser field fluctuations on coherent population trapping," *J. Phys. B* **15**, 3997-4015 (1982).
5. M. Fleischhauer and T. Richter, "Pulse matching and correlation of phase fluctuations in a Λ system," *Phys. Rev. A* **51** 2430-2442 (1995).
6. R. Walser and P. Zoller, "Laser-noise-induced polarization fluctuations as a spectroscopic tool", *Phys. Rev. A* **49**, 5067-5077 (1994).
7. M. Martinelli, P. Valente, H. Failache, D. Felinto, L.S. Cruz, P. Nussenzveig, A. Lezama, Phys. Rev.A 69, 043809 (2004)
8. L.S. Cruz, D. Felinto, J.G. Aguirre Gomez, M. Martinelli, P. Valente, A. Lezama, and P. Nussenzveig, "Laser-noise-induced correlations and anti-correlations in electromagnetically induced transparency," *Eur. Phys. J.* D **41**, 531-539 (2007).
9. V.A. Sautenkov, Y.V. Rostovtsev, M.O. Scully, " ," *Phys. Rev. A* **72**, 065801 (2005), quant-ph/0508026.
10. G.O. Ariunbold, V.A. Sautenkov, Y.V. Rostovtsev, M.O. Scully, " ," arXiv:quant-ph/0603025 (2005).