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Switching between photon-photon correlations and Raman anticorrelations in a coherently prepared Rb vapor

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We have experimentally observed switching between photon-photon correlations and anticorrelations between two orthogonally polarized laser beams in an electromagnetically induced transparency configuration in Rb vapor. The correlation and anticorrelation switching occurs at a specific magnetic field strength.

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Interaction of macroscopic laser fields with a resonant atomic three-level Lambda system has been the focus of recent research in quantum optics. In particular, interesting phenomena such as photon-photon correlation, phase squeezing, and new entangled states of the radiation field have been studied [1–5]. Sub-Poissonian statistics and a reduction of noise below photonic short noise have been demonstrated [4].

A new bright source of entangled photon states with controllable coherent time has been demonstrated [3] by employing parametric generation with counterpropagating electromagnetic waves in Rb vapor. The photon statistics of the light emitted from an atomic ensemble into a single field mode of an optical cavity has been studied in Ref. [6], and a smooth transition from bunching to antibunching has been experimentally demonstrated by changing the number of atoms in the cavity.

In this report, we study intensity correlations and anticorrelations of optical fields propagating through a dense rubidium vapor. The main result of the paper is shown in Fig. 1. For lower level coherence between Zeeman sublevels prepared by laser beams with orthogonal polarizations [Fig. 1(a)], we observe that the intensity fluctuations of two laser beams are correlated under the condition of electromagnetically induced transparency (EIT) [see Fig. 1(b)] and anticorrelated when two-photon detuning is introduced [see Fig. 1(c)]. That is, we have observed an interesting transition between correlation and anticorrelation of fields by changing two-photon detuning. The two-photon spectral width of this transition is narrower than the width of the EIT window. A theoretical approach similar to that developed in Refs. [7,8] has been used to explain the observed results.

An experimental setup is shown in Fig. 1(a). All measurements have been performed with an external-cavity diode laser (ECDL) tuned to the center of the Doppler broadened D_1 line $[5S_{1/2}(F=2)\leftrightarrow 5P_{1/2}(F'=1)]$. The output laser beam is split into two by a beam splitter, then the polarization of the one of the beams is rotated by a $\lambda/2$ wave plate, and these two orthogonally linear polarized beams are combined together by a polarizing beam splitter (PBS). After the $\lambda/4$ wave plate, the beam is a combination of two orthogonal circularly polarized optical fields which induce a ground state Zeeman coherence in Rb atoms. A simplified Λ scheme is depicted in insets of Figs. 1(b) and 1(c). A glass cell ($l=7.5$ cm) with Rb vapor at density 10^{12} cm^{-3} has been installed in a two-layer magnetic shield.

After the cell, the transmitted laser beams with opposite circular polarizations are separated by a second $\lambda/4$ wave plate and another polarizing beam splitter. Transmitted laser beams were focused on fast photodiodes (PDs) ET 2030A (Electro-Optics Technology) with frequency bandwidth 75 kHz–1.2 GHz. The optical path lengths for both beams are the same. Signals from PDs are analyzed by a digital

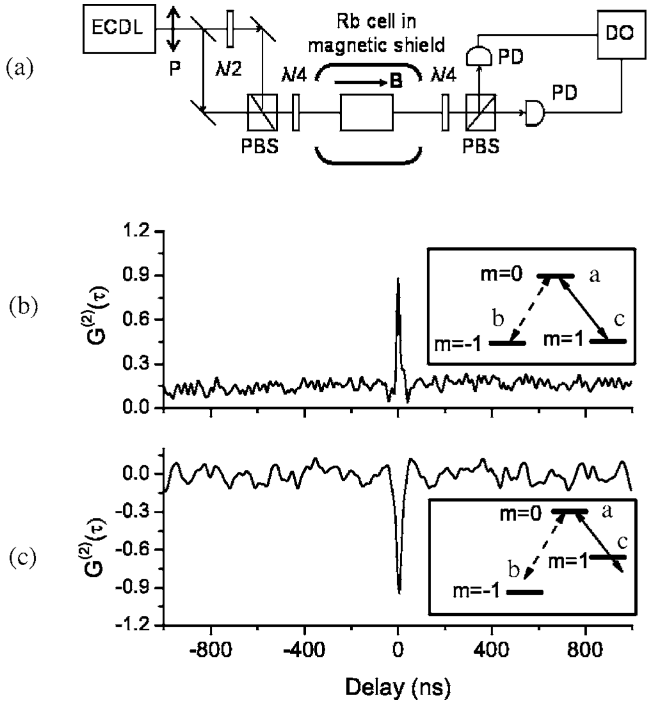

FIG. 1. (a) Experimental setup. ECDL is the external-cavity diode laser, P is the polarizer, PBS is the polarizing beam splitter, PD is the photodiode, DO is the digital oscilloscope. Intensity correlation functions, $G^{(2)}(\tau)$, are shown corresponding to two cases: (b) no magnetic field, EIT, and (c) with magnetic field, $B=-0.47$ G. The insets show the simplified energy levels without and with magnetic field.

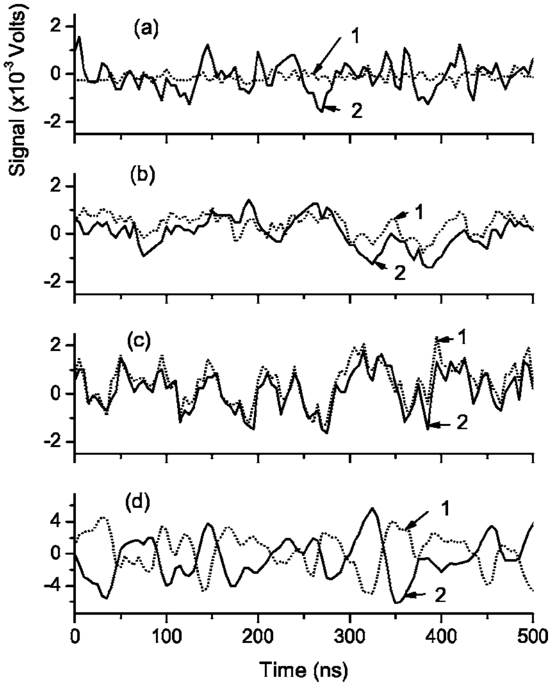

FIG. 2. Wave forms from photodetectors with optical power of laser beams at front window of Rb cell is 0.5 mW. The fluctuaions of intensity of (a) one beam (the second is blocked) before and after the cell, (b) two spatially separated beams, (c) two coinciding beams without magnetic field ($B=0$) at the EIT, zero two-photon detuning and (d) for magnetic field $B=-0.47$ G.

oscilloscope (DO) (Agilent 54624A with frequency bandwidth 100 MHz).

At the optical power of each beam at the entrance window of the Rb cell is 0.5 mW, beam diameters 0.1 cm, we vary a magnitude of longitudinal magnetic field and observe change in transmission. Linear transmission is less than 1%, and at the maximum of EIT transmission, it is 0.63. The measured full width at half maximum (FWHM) is 0.86 G, which is five times broader than for a low power limit 0.16 G, i.e., the width of EIT is determined by strong power broadening. By using ground state Zeeman splitting $\Delta\omega/2\pi_B=0.7$ MHz/G, one can estimate the spectral width of the EIT resonance of 1.2 MHz that are several times narrower than natural FWHM of hyperfine transitions 6 MHz and Rabi frequency.

To study fluctuations of optical fields transmitted through the dense Rb vapor, we have registered the dependence of the intensities of both optical beams on time, $\langle I_{1,2}\rangle+\delta I_{1,2}(t)$. Here $\langle I_{1,2}\rangle$ are the average intensities of the laser beams, and $\delta I_{1,2}(t)$ are the time dependent intensity fluctuations shown in Fig. 2. Data presented in Fig. 2 are a part of the 10 μsec recorded data. The signal in volts is proportional to laser intensity as 500 V/W. Wave forms shown in Fig. 2(a) are obtained under the conditions that one of the beams is blocked before the cell and there is no magnetic field ($B=0$). The first curve shows intensity fluctuations of the optical beam before it goes into the cell. It has practically no amplitude noise, and in order to see optical intensity noise above the photodetector noise, the optical power has to be increased at least three times. The second curve (with a larger wave form amplitude) shows excess noise of transmitted optical fields induced by the dense Rb vapor.

Wave forms in Fig. 2(b) show intensity fluctuations of two separated optical beams. Beams are separated by a tilted glass plate (an incident angle is close to the Brewster angle) with good quality parallel optical surfaces. Distance between beams is 0.3 cm, which is bigger than the beam diameters. One can see that the vapor induced noise is slightly correlated. Correlation increases when separation is reduced. Strong correlation between signals is shown in Fig. 2(c) under resonance EIT conditions. In Fig. 2(d), wave forms are recorded with two-photon detuning by applying a magnetic field $B=-0.47$ G.

One can see from Fig. 2 that there are strong correlations and anticorrelations between beams governed by the EIT condition. The correlation function $G^{(2)}(\tau)$ between intensities of two optical beams is calculated by

$$G^{(2)}(\tau)=\frac{\langle\delta I_1(t)\delta I_2(t+\tau)\rangle}{\sqrt{\langle[\delta I_1(t)]^2\rangle\langle[\delta I_2(t+\tau)]^2\rangle}}, \qquad (1)$$

where averaging over the time is defined as $\langle Q(t)\rangle=\int_t^{t+T}Q(t)dt/T$, τ is the selected time delay between the recorded signals, T is the time of integration, in our case $T=10$ μs.

In Fig. 1(b), the curve is calculated by using wave forms recorded under resonance EIT condition ($B=0$). The correlation peak at delay time $\tau=0$ has an amplitude of 0.9 and the background average value near 0.15. Figure 1(c) demonstrates a pronounced modification of wave forms due to two-photon detuning (applied magnetic field $B=-0.47$ G) showing that the wave forms are anticorrelated. For the reduced optical power, the width of the correlation peaks has decreased. The widths of the peaks is associated with the saturated width of resonance in Rb vapor absorption (a single-photon resonance) [9].

To study the role of coherence and to ensure that the results obtained are related to the interaction between optical beams, we perform experiments with separated beams. The results of analysis for power of 0.5 mW show that the correlation $G^{(2)}(\tau)$ obtained with spatially separated beams has the background 0.3 and a correlation peak with magnitude 0.7 at the delay $\tau=0$. When we reduce the spatial separation between beams, the contrast and the magnitude of the correlation pick is increased.

We perfom a set of measurements of $G^{(2)}(0)$ for different values of the magnetic field B. The correspondent dependence vs magnetic field for optical powers 0.5 mW and 0.25 mW are shown in Fig. 3. At zero magnetic field ($B=0$), the correlation between $\delta I_1(t)$ and $\delta I_2(t)$ is close to 0.9. The correlation decreases with increasing of the magnetic field, it goes through zero, and then it reaches magnitude -0.9.

Intensity correlation $G^{(2)}(0)$ demonstrates a resonancelike behavior on the change of magnetic field. The data was fit by Lorentzian functions. The widths of these resonances are 0.24 and 0.16 G correspondingly, which is nearly four times narrower than the width of the EIT window at the same optical power. The EIT width (FWHM) increases from

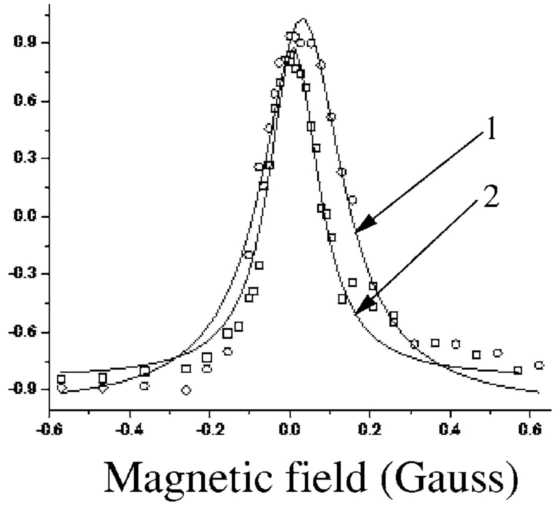

FIG. 3. Correlation $G^{(2)}(0)$ versus magnetic field B in Gauss (two-photon detuning). Circles and solid curve 1 correspond to optical power 0.5 mW, squares and solid curve 2 to optical power 0.25 mW. The solid curves are obtained by fitting the experimental points by Lorentzian functions.

0.65 G to 0.86 G with optical power of each laser beam from 0.25 to 0.5 mW. The smallest measured width of the correlation resonance coincides with the width of the EIT resonance at the low power limit 0.16 G.

The intensity fluctuations can be described in various ways, e.g., by the Heisenberg-Langevin approach, a Fokker-Planck analysis, the quantum regression theorem, etc. [18], each provides it's own insights to the classical and quantum fluctuations in the system under investigation. Intensity correlations and sub-Poissonian statistics were observed with two lasers in EIT regime [4,10]. In nonlinear magnetorotation [11], the quadrature squeezing theoretically predicted [12,13] has been experimentally demonstrated [14].

In the present experiment, we have two beams of strong laser radiation with different polarizations interacting with the atomic system [as shown in Fig. 1(a)]. There are two mechanisms by which the intensity fluctuations can be generated in an atomic medium. One is related to the phase fluctuations of laser field (a linear effect) [15] and the second is the four-wave mixing of vacuum modes (a nonlinear effect) [17]. It was shown that the efficiency of phase noise (PhN) conversion to intensity noise (IN) is smaller at higher intensity, when nonlinear processes are dominant. The PhN-to-IN conversion phenomenon was used for noise spectroscopy of resonance medium [15]. Noise spectroscopy of EIT is studied in Ref. [16]. Also, excess noise was observed under EIT conditions. We studied correlations on delay time and dependence of the maximal correlation on two-photon detuning. In our case, the optical density has been large and noise spectrum is defined by the shape of spectral hole due to one-photon saturation [9].

Physical insight into this process is gained on the basis of a simplified approach treating the laser fields classically, using the density matrix for treating the resonance atomic response, and taking into account propagations that are essential for the problem. The laser beams are in the resonance three-level medium as depicted in Fig. 1.

Indeed, the polarizations and coherence in the three-level system are given [18] by

$$\rho_{cb} = -\frac{\Gamma_{ca}+\Gamma_{ab}}{2\Gamma_{ca}\Gamma_{ab}}\frac{\Omega_1\Omega_2}{\Gamma_{cb}+\dfrac{|\Omega_2|^2}{\Gamma_{ab}}+\dfrac{|\Omega_1|^2}{\Gamma_{ca}}}, \qquad (2)$$

$$\rho_{ab} = -i\frac{n_{ba}\Omega_1+\rho_{cb}\Omega_2}{\Gamma_{ab}}, \quad \rho_{ca} = i\frac{n_{ca}\Omega_2+\rho_{cb}\Omega_1}{\Gamma_{ca}}, \qquad (3)$$

where $n_{ba}=n_b-n_c$, $n_{ca}=n_c-n_a$, $\Gamma_{ab}=\gamma_{ab}+i(\omega_{ab}-\nu_1)$, $\Gamma_{ca}=\gamma_{ca}-i(\omega_{ac}-\nu_2)$, $\Gamma_{cb}=\gamma_{cb}+i(\omega_{cb}-\nu_1+\nu_2)$, where $\omega_{\alpha\beta}$ are the atomic frequencies, n_a, n_b, and n_c are the populations in levels a, b, and c, correspondingly, and $\nu_1(t)=\nu_2(t)$ are the instant frequency of laser radiation in both beams having orthogonal polarizations. Practically all population is distributed between levels b and c, $n_b=n_c\simeq 1/2$, no population is in level a, $n_a=0$. The equations for field propagation are

$$\frac{\partial\Omega_1}{\partial z} = -i\eta_b\rho_{ab}, \quad \frac{\partial\Omega_2}{\partial z} = -i\eta_c\rho_{ac}, \qquad (4)$$

where $\eta_b=\nu_1 N\wp_b/(2\epsilon_0 c)$, $\eta_c=\nu_2 N\wp_c/(2\epsilon_0 c)$ are the coupling constants, N is the density of the medium, ϵ_0 is the permittivity of the vacuum, and c is the speed of light in the vacuum.

Depending on the detunings for optical fields ($\nu_1-\omega_{ab}$ and $\nu_2-\omega_{ac}$), which are different for different polarizations, the amplitude fluctuations for fields occurs in phase or π out of phase. When two fields are in the resonance with atomic transitions ($\nu_1-\omega_{ab}=\nu_2-\omega_{ac}$), phase fluctuation of the laser field, as it can be seen from Eqs. (2) and (3), leads to detuning from the resonance, but one-photon detunings for both fields are the same, so the change of intensities are in the same direction, and the fields are correlated. When the detuning is included ($\nu_1-\omega_{ab}\neq\nu_2-\omega_{ac}$), then the change of absorption is different for these two beams, see Eqs. (2) and (3). One field frequency is tuning closer to the resonance but another is tuning out of resonance. The last gives rise to anticorrelations. The time scale to establish correlation or anticorrelation between intensities of laser beams depends on long-lived coherence relaxation between magnetic sublevels. An interesting result is that the spectral width of the correlation function is more tolerant of the power broadening, giving us a four times narrower peak than the EIT width. The second mechanism, using four-wave mixing, gives us a nonlinear contribution to the intensity fluctuations. Let us note that both mechanisms lead to correlation at the EIT condition; correlated intensities can be also considered from the point of view of matched pulses [19].

A useful theoretical approach for this situation is the technique developed for the correlated emission lasers (CEL) [7,8]. The system is practically the same, but instead of a V scheme, we have here a Lambda system, and the basic processes, described in terms of the CEL analysis, are locking and unlocking. The basic equation describing the obtained results for the angle θ, which is the phase deference of two radiation modes, is given by

$$\dot{\theta} = a - b \sin \theta + \mathcal{F}(\theta) \tag{5}$$

where $\mathcal{F}(\theta) = \cos(\theta/2) F_{-}(\theta) + \sin(\theta/2) F_{+}(\theta)$, $F_{\pm}(\theta)$ are the Langevin forces. When two modes are locked, their intensities start correlating [8].

We performed numerical simulations by using the quantum regression theory taking the same values of the parameters as in the current experiments and the results will be published elsewhere [20].

The correlation peak in Fig. 1(b) is quite narrow, just $\tau = 18$ ns. The corresponding frequency spectrum has a width 18 MHz that is an order more than EIT width 1.2 MHz. We have observed the noise spectrum of laser radiation after the cell directly with a spectrum analyzer. Probably, correlated spectral components of coupled optical fields find appropriate degenerated Λ systems. The magnetic field changes correlations between the wave forms. In Fig. 1(c), one can see the anticorrelation peak and some fluctuations near zero level ($B = -0.47$ G). On the slope of the EIT resonance, phase noise should be more efficiently converted to the intensity noise. In Fig. 2, one can see that the noise on the slope of the EIT resonance is more pronounced as compared to the EIT resonance.

In conclusion, we report an experimental observation of intensity correlations and anticorrelations of coupled fields in a dense Rb vapor where lower level coherence is created between Zeeman sublevels by two laser beams with orthogonal polarizations. Intensity fluctuations induced by a resonant medium are correlated under resonance EIT condition and anticorrelated at some value of two-photon detuning. Narrow correlation and anticorrelation peaks are associated with frequencies above the EIT width and the natural optical width. Dependence of correlations on a magnetic field (two-photon detuning) show resonance behavior. The resonances are nearly four times narrower than the width of the observed EIT resonances.

Correlation properties of coupled fields in the Λ scheme can be used to reduce noise and improve performance of EIT-based atomic clocks and magnetometers. The PhN-to-IN conversion is an important physical process limiting the accuracy. In EIT atomic clocks and magnetometers [21], it is possible to avoid the contribution of the atomic medium induced excess intensity noise. In the Λ EIT, we demonstrated that wave forms of the transmitted optical field can be strongly correlated. If one would detect coupled fields separately by two independent photodetectors and then subtract signals, the noise would be reduced to photonic shot noise or even less (sub-Poissonian photon statistics of coupled optical fields).

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