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Observation of cross-phase shift in hot atoms with quantum coherence

Hong Chang, Yingjie Du, Jingqin Yao, Changde Xie and Hai Wang(*)
The State Key Laboratory of Quantum Optics and Quantum Optics Devices
Institute of Opto-Electronics, Shanxi University - Taiyuan, 030006, PRC

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PACS. `42.50.Gy` – Effects of atomic coherence on propagation, absorption, and amplification of light; electromagnetically induced transparency and absorption.
PACS. `42.65.Hw` – Phase conjugation; photorefractive and Kerr effects.

Abstract. – We directly measure the cross-phase shift and nonlinear refractive index of a three-level Λ-type hot atomic coherence system inside an optical ring cavity. The cross-phase nonlinear index of refraction n_2 is significantly enhanced and sharply changed when the conditions of atomic two-photon resonance are closed. The cross-phase shift of π induced by controlling light on the probe wave has been observed under a relatively low controlling power of 16.2 mW. The system is valuable in developing optical devices for the optical information process.

Kerr-type nonlinearity and conditional phase shift have very useful applications in optical Kerr shutters [1], generation of squeezed states [2, 3], all-optical switch [4], quantum nondemolition measurements [5], quantum logical phase gate [6] and complete quantum teleportation [7]. It is a common pursuit to achieve high optical nonlinearity with low light intensity. Especially, for the applications in future densely integrated optical circuits and quantum logical elements, low-light-power operations of devices are absolutely needed [4,6,8]. Electromagnetically induced transparency (EIT) in multilevel atomic systems inside an optical ring cavity provides an effective way to lower the intensity of the coupling light and to measure the Kerr nonlinear index of refraction [4]. Recently, the enhanced Kerr nonlinearity related to self-phase modulation in EIT system inside a cavity has been measured, and based on it, an all-optical switching has been demonstrated [9]. Kerr nonlinearity related to cross-phase modulation in a four-level atomic system has also been theoretically proposed by Schmidt and Imamoglu [1], and experimentally demonstrated by the group of Zhu [10]. A full π phase shift used for all-optical switching has been experimentally achieved via cross-phase modulation in a microstructured fiber with a controlling power of 3 W [11]. Grangier and his co-workers have realized QND measurement via the two-photon cross-phase modulation effect in a three-level atomic system under the far-from-resonance condition [12]. The group of Mlynek observed optical bistability from three-level atoms with the use of a coherent nonlinear mechanism [13]. Hau *et al.* completed an experiment of light speed reduction to 17 m/s by

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(*) E-mail: `wanghai@sxu.edu.cn`

means of EIT in ultracold atomic gas. In this experiment, an inferred (not directly measured) giant cross-phase nonlinear refractive index of $n_2 = 0.18\,\mathrm{cm}^2/\mathrm{W}$ is obtained [14]. However, the parameter dependences of the cross-phase nonlinearity have not been experimentally and directly measured in a three-level atomic medium near EIT resonance so far, to the best of our knowledge. Generally, it is a difficult task to directly measure the cross-phase shift and the nonlinear index of refraction under the condition of near atomic resonance because of the existence of the large linear and nonlinear absorption effects.

In this letter, we present an experimental observation to the cross-phase shift in a three-level coherent hot atomic system inside an optical ring cavity. Due to applying the intracavity EIT effect, the controlling light power needed for achieving a full π-conditional phase shift on the probe light is only 16.2 mW. The cross-phase nonlinear index of refraction as a function of controlling light frequency detuning was experimentally measured.

We consider a three-level Λ-type ^{87}Rb atomic system and the D_1 line of atomic levels are applied (inset of fig. 1). $F = 1$ (state $|1\rangle$) and $F = 2$ (state $|3\rangle$) states of $5S_{1/2}$ serve as the two lower states and $F' = 2$ (state $|2\rangle$) state of $5P_{1/2}$ as the upper state. The controlling laser beam with frequency ω_c and Rabi frequency $\Omega_\mathrm{c} = -\mu_{23}E_\mathrm{c}/\hbar$ couples states $|3\rangle$ and $|2\rangle$, while the probe beam with frequency ω_p and Rabi frequency $\Omega_\mathrm{p} = -\mu_{21}E_\mathrm{p}/\hbar$ interacts with states $|1\rangle$ and $|2\rangle$. E_c and E_p are the amplitudes of the controlling and the probe fields, μ_{23} and μ_{21} are the dipole matrix elements between states $|2\rangle$ and $|3\rangle$, and states $|1\rangle$ and $|2\rangle$, respectively. The frequency detunings of the controlling light and the probe light are, respectively, $\Delta_\mathrm{c} = \omega_\mathrm{c} - \omega_{23}$ and $\Delta_\mathrm{p} = \omega_\mathrm{p} - \omega_{21}$, where ω_{23} is the atomic transition frequency between states $|3\rangle$ and $|2\rangle$, and ω_{21} between states $|1\rangle$ and $|2\rangle$. For a relatively strong controlling light, $\Omega_\mathrm{c} \gg \Omega_\mathrm{p}$, most atoms will be optically pumped into the ground level $|1\rangle$. The susceptibility χ of the probe transition can be modified by the controlling light due to EIT effect [15]. Performing a power series expansion of eq. (3) in ref. [15] for the quantity Ω_c^2, the susceptibility is approximated as

$$\chi = \chi^{(1)} + 3\chi^{(3)} = \frac{iN\mu_{21}^2}{\hbar}\frac{1}{\gamma - i\Delta_\mathrm{p}}\left[1 - \frac{|\Omega_\mathrm{c}|^2/4}{(\gamma - i\Delta_\mathrm{p})\big(\Gamma_3 - i(\Delta_\mathrm{p} - \Delta_\mathrm{c})\big)}\right], \tag{1}$$

where $\gamma = (\Gamma_1 + \Gamma_2 + \Gamma_3)/2$, Γ_1 and Γ_2 are the spontaneous decay rates of the excited state $|2\rangle$ to the ground states $|1\rangle$ and $|3\rangle$, respectively; Γ_3 is the nonradiative decay rate between the two ground states. N is the atomic density in the cell. The first term in eq. (1) is linear susceptibility and the second term expresses the cross-phase modulation induced by the controlling light. The refractive index of the probe light is given by $n = 1 + n_2 I_\mathrm{c}$, where I_c is the intensity of the controlling light, and the cross-phase nonlinear refractive index n_2 is related to $\chi^{(3)}$ by $n_2 = 12\pi^2\,\mathrm{Re}[\chi^{(3)}]/n_0^2 c$ [16], where $n_0 \approx 1$. For the three-level Λ-type system, the first-order Doppler effect is eliminated by copropagation of the controlling and the probe light beams in the atomic cell [15].

Because the nonlinear index of refraction strongly depends on the intensity of the controlling light (I_c), when a nonlinear medium is placed inside an optical ring cavity and the length of the cavity is scanned, the nonlinear index of refraction n_2 will introduce a cross-phase shift on the probe light. The cavity phase detuning $\Delta\Phi$ for the probe light equals

$$\Delta\Phi = 2\pi\frac{L}{\lambda} + \Delta\phi + \Phi_0 - 2m\pi, \tag{2}$$

where L is the length of the optical cavity; λ is the wavelength of the probe light; m is an

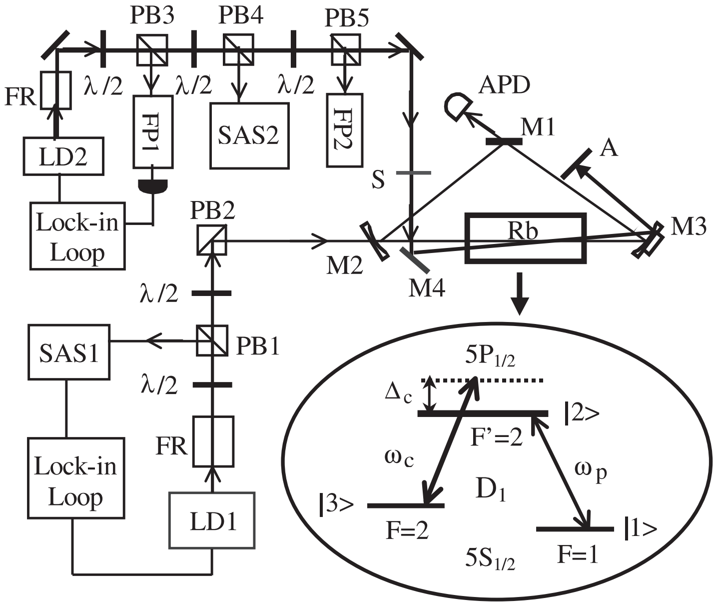

Fig. 1 – Experimental setup and diagram of atomic levels (inset). LD1 and LD2 are the probe and controlling lasers, respectively; PB: polarizing beam splitter; $\lambda/2$: half-wave plate; FR: Faraday rotator; FP: Fabry-Perot cavity; APD: avalanche photodiode detector; SAS: saturation absorption spectroscopy.

integer; Φ_0 is the phase offset of the cavity. The cross-phase shift $\Delta\phi$ of the probe field is given by

$$\Delta\phi = 2\pi\frac{l}{\lambda}n_2 I_\mathrm{c} = 2\pi\frac{l}{\lambda}n_2\frac{P_\mathrm{c}}{A_\mathrm{c}}\,, \tag{3}$$

where l is the length of the atomic cell, I_c and P_c, respectively, express the intensity and power of the controlling light, and A_c stands for the cross-section area of the controlling light. The resonance peaks in transmission appear when the cavity phase detuning $\Delta\phi = 0$, which corresponds to the resonances of probe light at some certain cavity lengths. The cross-phase shift $\Delta\phi$ can be directly measured from the resonance peak shift $\Delta L = L_\mathrm{r} - L'_\mathrm{r}$,

$$\Delta\phi = 2\pi\frac{\Delta L}{\lambda}\,, \tag{4}$$

where L'_r and L_r are the lengths of the cavity with the cross-phase shift ($\Delta\phi \neq 0$) and without the cross-phase shift ($\Delta\phi = 0$), respectively. After $\Delta\phi$ is experimentally measured, n_2 can be obtained from eqs. (3) and (4) directly.

The experimental setup is shown in fig. 1. The lasers for both the controlling and the probe light are the extended-cavity diode lasers with the output power of $\sim 30\,\mathrm{mW}$ (LD2 and LD1). The polarizations of the controlling light and the probe light are orthogonal. A part (about 20%) of the probe light is split by a polarizing beam splitter (PB1) to a saturation absorption spectroscopy (SAS1) setup to stabilize the frequency of the probe laser. Another part of the probe beam is injected into the optical ring cavity. The intensity of the probe light beam can be adjusted by a half-wave plate and PB2. The ring cavity consists of three mirrors; the flat

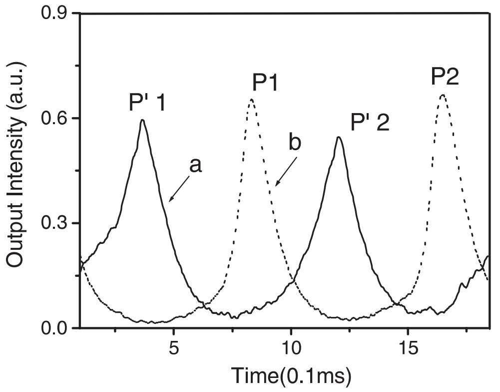

Fig. 2

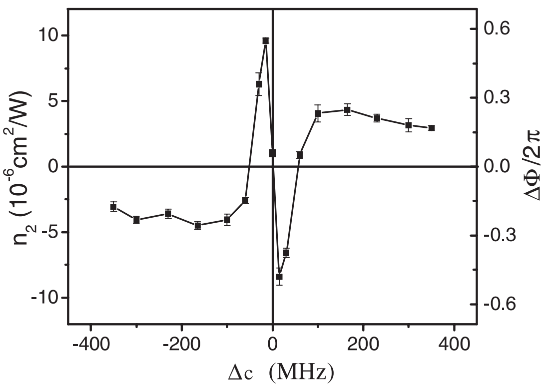

Fig. 3

Fig. 2 – Cavity transmission profile for $\Delta_\mathrm{p} = 0$, $\Delta_\mathrm{c} = -15\,\mathrm{MHz}$ and $P_\mathrm{c} = 16.2\,\mathrm{mW}$ with controlling light on (a) and with controlling light off (b).

Fig. 3 – Measured nonlinear index of refraction n_2 *vs.* frequency detuning of controlling light Δ_c for $P_\mathrm{c} = 16.2\,\mathrm{mW}$ and $\Delta_\mathrm{p} = 0$.

mirror M1 and the concave mirror M2 (the radius of curvature $R = 10\,\mathrm{cm}$) have about 0.5% and 5% transmissions, respectively. The concave mirror M3 ($R = 10\,\mathrm{cm}$) is mounted on a piezoelectric transducer (PZT) with reflectivity about 99.5%. The finesse of the empty cavity is about 100 with a free spectral range of 870 MHz. The geometric length of the cavity is about 34.5 cm. The rubidium vapour cell (5 cm in length and heated to 95 °C) with wrapped μ metal sheet is placed inside the cavity. The controlling beam is successively split by polarizing beam splitters PB3, PB4 and PB5 to two Fabry-Perot cavities (FP1 and FP2) and a saturation absorption spectroscopy (SAS2) setup to lock and monitor the frequency detunings of the controlling laser. A small mirror M4 with high reflectivity at 795 nm is placed in the cavity and is used for reflecting the controlling light into the atomic cell and across the probe light. The reflected controlling light transmit through the Rb vapor cell and the probe light is not blocked by M4 using a delicate design. The controlling light is misaligned by a small angle (less than 1 degree) and a diaphragm (A) is inserted between mirrors M3 and M1 to avoid its circulation inside the optical cavity. The radii of the controlling and probe beams are estimated to be 600 μm and 130 μm, respectively. With the insertion losses of the reflection from two windows of the atomic cell, the cavity finesse (with rubidium atoms far from resonance) is degraded to about 32 from 100. The intensity of the controlling light entered into the atomic cell can be changed by a half-wave plate and PB5, its frequency is controlled precisely by locking to Fabry-Perot cavity FP1, and the frequency detuning can be measured by SAS2 and FP2.

We first tune and lock the probe light to the resonant frequency of the transition ($5S_{1/2}$, $F = 1$–$5P_{1/2}$, $F' = 2$), *i.e.*, $\Delta_\mathrm{p} = 0$. Then, the controlling light is tuned to the near-resonant frequency of the transition ($5S_{1/2}$, $F = 2$–$5P_{1/2}$, $F' = 2$) and is locked on too. The controlling beam can be turned on or off by an electromagnetic switch S. The length of the cavity across resonance is scanned by applying a ramp voltage to the PZT mounted upon the mirror M3 and the cavity transmission is directly measured by an avalanche photodiode detector (APD). The peak value of the intracavity power (with cavity on resonance) is estimated to be about 130 μW, which corresponds to a Rabi frequency $\Omega_\mathrm{p} = 2\pi \times 31\,\mathrm{MHz}$. The injected power of the controlling light into the atomic cell is about 16.2 mW, which corresponds to an average Rabi frequency of $\Omega_c = 2\pi \times 75\,\text{MHz}$. When the controlling light is turned off and the cavity length is scanned linearly with time, two transmission peaks (P1, P2) are observed. However, when the controlling light of $P_c = 16.2\,\text{mW}$ with $\Delta_c = -15\,\text{MHz}$ is turned on, the transmission peaks P1 and P2 move to P′1 and P′2, respectively. The distance between the two peaks (P1 and P2 or P′1 and P′2) is equal to the wavelength λ of the probe light. The moved direction of the resonance peak gives the sign of n_2. As the cavity length is scanned from longer to shorter, if n_2 is positive, the cavity length at resonance peak will turn into shorter and the resonance peak will move forward along the direction of scanning time. If n_2 is negative, the motion of the resonance peak will be in the opposite direction. The nonlinear cross-phase shift $\Delta\phi$ of the probe field can be directly measured from the resonance peak shift ΔL between P1 and P′1. From fig. 2, we measured a resonance peak shift $\Delta L \approx 0.5\lambda$; this means a nonlinear cross-phase shift of π order is obtained (eq. (4)). For the power of the controlling light $P_c = 16.2\,\text{mW}$ with a waist radius of $600\,\mu\text{m}$ in the center of the cell, we calculate the cross-phase nonlinear index of refraction $n_2 = 9.6 \times 10^{-6}\,\text{cm}^2/\text{W}$ from eqs. (3) and (4). The calculated absorption coefficient of atomic vapour from the measured finesse of the optical cavity is about 50%.

Figure 3 shows the measured cross-phase shift $\Delta\phi$ and the cross-phase nonlinear index of refraction n_2 as functions of detuning Δ_c of the controlling light with $\Delta_p = 0$ and $P_c = 16.2\,\text{mW}$. It is shown that near the resonant frequency of the controlling light, $\Delta\phi$ and n_2 are greatly enhanced and n_2 is sharply changed due to atomic coherence. The experimental result of the function shape and magnitude is consistent with the calculated result from eq. (1) in which the Doppler broadening is considered. The peak values of $\Delta\phi$ and n_2 were measured at $\Delta_c = \pm 15\,\text{MHz}$; for $\Delta_c = -15\,\text{MHz}$, we have $\Delta\phi = 1.1\pi$ and $n_2 = 9.6 \times 10^{-6}\,\text{cm}^2/\text{W}$ and for $\Delta_c = 15\,\text{MHz}$, $\Delta\phi = -0.96\pi$ and $n_2 = -8.4 \times 10^{-6}\,\text{cm}^2/\text{W}$.

In summary, we have directly measured the cross-phase Kerr nonlinear index n_2 in a three-level EIT system with hot Rb atoms inside an optical ring cavity. The measured n_2 is much lower than that observed in the ultra-cold atomic system [14] due to the influences of Doppler broading and laser linewidth. The theoretical expectation from eq. (1) which considers these influences is consistent with our experimental results. The scheme can eliminate the contribution from linear and nonlinear absorption and thus can be used for direct measurement of the cross-phase shift. The phase shift of π order is achieved with a controlling light power of 16.2 mW in a three-level Λ-type hot atomic coherence system. The presented system can be exploited to develop optical devices such as optical shutter and so on.

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REFERENCES

[1] Schmidt H. and Imamoglu A., *Opt. Lett.*, **21** (1996) 1936.

[2] Reid M. D. and Walls D. F., *Phys. Rev. Lett.*, **55** (1985) 1288; *Phys. Rev. A*, **31** (1985) 1622.

[3] Kumar P. and Shapiro J. H., *Phys. Rev. A*, **30** (1984) 1568.

[4] Xiao M., Wang H. and Goorskey D., *Opt. Photon. News*, **13** (No. 9) (2002) 44; **13** (No. 12) (2002) 33.

[5] Poizat J. Ph. and Grangier P., *Phys. Rev. Lett.*, **70** (1993) 271.

[6] Turchette Q. A., Hood C. J., Lange W., Mabuchi H. and Kimble H. J., *Phys. Rev. Lett.*, **75** (1995) 4710.

[7] Vitali D., Fortunato M. and Tombesi P., *Phys. Rev. Lett.*, **85** (2000) 445.

[8] Harris S. E. and Yamamoto Y., *Phys. Rev. Lett.*, **81** (1998) 3611.

[9] Wang H., Goorskey D. and Xiao M., *Phys. Rev. Lett.*, **87** (2001) 073601; *Opt. Lett.*, **27** (2002) 1354.

[10] Hoonsoo Kang and Yifu Zhu, *Phys. Rev. Lett.*, **91** (2003) 093601.

[11] Sharping J. E., Fiorentino M., Kumar P. and Windeler R. S., *Opt. Photon. News*, **13** (No. 12) (2002) 28.

[12] Grangier Philippe, Roch Jean-Francois and Roger Gerard, *Phys. Rev. Lett.*, **66** (1991) 1418.

[13] Mlynek J., Mitschke F., Deserno R. and Lange W., *Phys. Rev. A*, **29** (1984) 1297.

[14] Hau L. V., Harris S. E., Dutton Zachary and Behroozi Cyrus H., *Nature*, **397** (1999) 594.

[15] Yong-qing Li and Xiao M., *Phys. Rev. A*, **51** (1995) R2703.

[16] Boyd R. W., *Nonlin. Opt.* (Academic Press, New York) 1992.