Vol 14 No 6, June 2005
1009-1963/2005/14(06)/1120-05

Chinese Physics

Experimental observation of pump–probe spectra of caesium D_2 line with a vapour cell*

Wang Yan-Hua(王彦华), Yang Hai-Jing(杨海菁),
Zhang Tian-Cai(张天才), and Wang Jun-Min(王军民)†

State Key Laboratory of Quantum Optics and Quantum Optics Devices, and Institute of Opto-Electronics,
Shanxi University, Taiyuan 030006, China

(Received 25 November 2004; revised manuscript received 21 January 2005)

Pump–probe spectra of caesium D_2 line are experimentally investigated in a Cs atomic vapour cell with co-propagating orthogonal linearly-polarized pump and probe laser beams. Absorption-reduction dips duo to electromagnetically induced transparency (EIT) in multi-Λ-type Zeeman sublevels of 6 $S_{1/2}$ F=3–6 $P_{3/2}$ F'=2 hyperfine transition and absorption-enhanced peaks due to electromagnetically induced absorption (EIA) in 6 $S_{1/2}$ F=4–6 $P_{3/2}$ F'=5 hyperfine transition are demonstrated. With detuned pump beam abnormal sign-reversed signals inside the EIT dip and the EIA peak are clearly observed.

Keywords: pump–probe spectroscopy, caesium atoms, atomic coherence, electromagnetically induced transparency (EIT), electromagnetically induced absorption (EIA)

PACC: 3280, 4262, 4250

1. Introduction

Atomic coherence and quantum interference have become a hot field in quantum optics in recent years. This has led to many interesting and fascinating effects or phenomena, such as amplification without inversion (AWI),[1] coherent population trapping (CPT),[2] electromagnetically induced transparency (EIT),[3] etc. The information of the coherent process between pump–probe fields and the atomic medium can be obtained via the probe beam's absorption. Pump–probe spectra become one kind of basic tool in this area. Many research works of atomic coherence were focused on three-level atomic systems, and most of such experiments were carried out in connection with the fine or hyperfine levels of atoms. Various atomic coherence properties in degenerate or nearly degenerate two-level systems consisting of Zeeman sublevels were also demonstrated. For example, recently the absorption enhancement due to electromagnetically induced absorption (EIA) was observed in degenerate two-level systems.[4–8] EIA has attracted extensive attention because of its large negative dispersion yielding super-luminal group velocity and other coherent properties.[9–16] Ref.[5] indicated three conditions for EIA: (1) degenerate ground states for forming a long-lived coherence in Zeeman sublevels; (2) $0 < F < F'$ (F and F' indicate the atomic momentum of the ground and the excited states) for not constructing CPT in the ground states; (3) closed transition. However, more detailed EIA theory[10,11] was presented considering the spontaneous coherence and it is well accepted that EIA is due to the transfer of coherence between degenerate excited states to ground states via spontaneous emission. Refs.[10,11] also pointed out that EIA is possible in an open system. The experiments have been carried out.[12–15] Maybe the above-mentioned second and third conditions are not necessary.

In this paper, pump–probe spectra of D_2 line in Cs atomic vapour cell are presented. Absorption-reduction dips due to EIT effect in multi-Λ-type Zeeman sublevels of Cs F=3–F'=2 degenerate two-level system, and absorption-enhanced peaks due to EIA ef-

---

*Project supported by the National Natural Science Foundation of China (Grant Nos 10434080 and 10374062), by the Key Scientific Project of Education Ministry of China (Grant No 204019), by the Research Funds for Youth Academic Leaders of Shanxi Province, and by the Research Founds for the Returned Overseas Scholars of Shanxi Province.

†E-mail: wwjjmm@sxu.edu.cn

fect in Cs F=4–F'=5 degenerate two-level system are experimentally demonstrated in pump–probe spectra. EIA in Cs F=4–F'=4 open transition is also demonstrated. With detuned pump laser abnormal sign-reversed signal appears inside the EIA peak and the EIT dip. To our knowledge, it is the first presentation of the absorption-enhanced peak inside the EIT dip in the case of Cs F=3–F'=2, 3 and 4 transitions. Qualitative analysis is given.

2. Experimental arrangement

Figures 1(a) and (b) show relevant Cs hyperfine levels. In the case of F=3–F'=2, 3, 4 transitions, the pump laser couples F=3 and F'=2 hyperfine levels with a detuning of Δ_C, while the probe laser scans across F=3 to F'=2, 3, 4 transitions (Fig.1(a)). In the case of F=4–F'=3, 4, 5 transitions, the pump laser drives F=4–F'=5 cycling transition with a detuning of Δ_C, while the probe laser scans across F=4 to F'=3, 4, 5 transitions (Fig.1(b)).

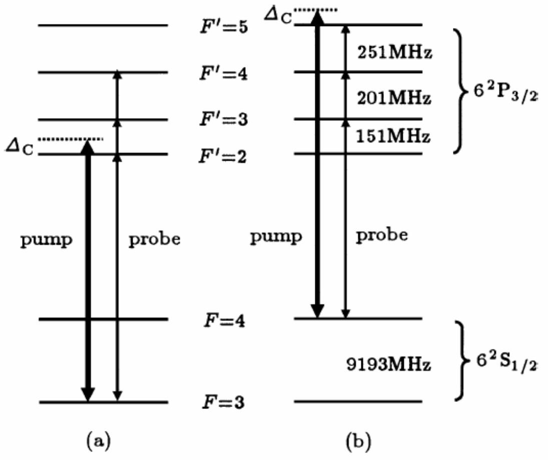

Fig.1. Relevant hyperfine levels and transitions of Cs atoms. The hyperfine splitting of the ground and excited states are marked in frequency unit. (a) The pump laser couples F=3 and F'=2 hyperfine levels with a detuning of Δ_C, while probe laser scans across F=3 to F'=2, 3, 4 transitions. (b) The pump laser drives F=4–F'=5 cycling transition with a detuning of Δ_C, while probe laser scans across F=4 to F'=3, 4, 5 transitions.

The scheme of our experimental apparatus is shown in Fig.2. A commercial grating external-cavity diode laser (ECDL) (Toptica DL100) and a self-made ECDL serve as the pump laser and probe laser, respectively. Their line-width is roughly 1MHz, which is much less than the natural line-width of the excited state $6^2P_{3/2}$ (5.2MHz). Both lasers' output beams pass through optical isolators (IsoWave, Model I-80-T5-L) with typical 35dB of isolation degree to avoid optical feedback, then are shaped to near circular by anamorphic prism pairs (not shown in Fig.2). A 40mm-long Cs vapour quartz cell inserted into a magnetic shield tube is utilized to weaken the influence of the geomagnetic field and other stray magnetic fields. Actively stabilizing the temperature of Cs cell is not performed in our experiment. The pump and probe beams co-propagate through the Cs cell with orthogonal linear polarizations (p polarization for the pump beam and s polarization for the probe beam, indicated as P and S in Fig.2). Two polarization-beam-splitting cubes (PBS) with typical extinction ratio of 50dB are used to combine and separate the pump and probe beams.

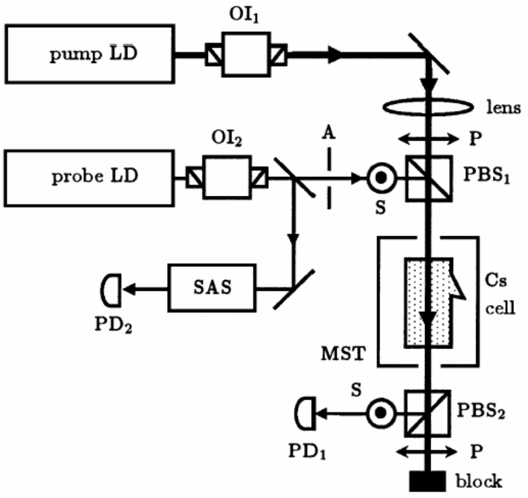

Fig.2. Schematic diagram of experimental setup. OI$_s$: optical isolators; PBS$_s$: polarization beam splitter cubes; P: p polarization; S: s polarization; A: aperture; MST: magnetic field shielding tube; SAS: saturation absorption spectrometer; PD$_s$: photodiodes.

In the region of the Cs cell, typical power for the pump beam and the probe beam are 25mW and ~10μW, respectively. To increase the pump intensity in the Cs cell a lens with focal length of f=200mm is used in the optical path. Typical spot diameters for the pump beam and the probe beam in Cs cell are ~ 2.2mm and ~1.5mm, respectively. Transmission of probe beam is detected with a photodiode (PD$_1$) and recorded by a digital oscilloscope (not shown in Fig.2) for analysis. An interferometer of saturation absorption spectra (SAS) is used to calibrate the probe detuning.

3. Experimental results and discussion

With the pump and probe beams co-propagating in Cs cell collinearly, the Doppler shifts for the pump and probe beams have the same quantity to the same moving atomic reference frames. As a result, all atoms, even though they have different velocity due to their thermal motion, will contribute to pump–probe spectra. Because the hyperfine splitting in the excited state $6\,^2\mathrm{P}_{3/2}$ is much smaller than the Doppler broadening (~ 500MHz) at room temperature, in contrast, the hyperfine splitting in the ground state $6\,^2\mathrm{S}_{1/2}$ is 9193MHz which is much larger than the Doppler broadening, so that hyperfine transitions of F=3–F'=2, 3, 4 and of F=4–F'=3, 4, 5 will be covered by two separated Doppler backgrounds.

3.1. The case of F=4–F'= 3, 4 and 5 transitions

In the case of F=4–F'=3, 4 and 5 transitions, we reasonably choose F=4–F'=5 cycling transition as a frequency reference point. The intense pump beam is tuned to F=4–F'=5 transition with a certain detuning, while the weak probe beam is scanned across F=4–F'=3, 4 and 5 transitions. In this way we have recorded corresponding pump–probe absorption spectra by use of photodiode PD1 (as in Fig.2) and a digital oscilloscope.

The pump–probe absorption spectra of F=4–F'=3, 4 and 5 transitions with roughly same pump intensity and different pump detuning are shown in Fig.3. The lowest curve in Fig.3 is the saturation absorption spectrum (SAS) with Doppler background, which is recorded by photodiode PD2 (as in Fig.2) and used to calibrate probe frequency. The positions of F=4–F'=5 cycling transition and F=4–F'=3 hyperfine transition, which is –452MHz away from the cycling transition, are marked with arrowed lines in Fig.3.

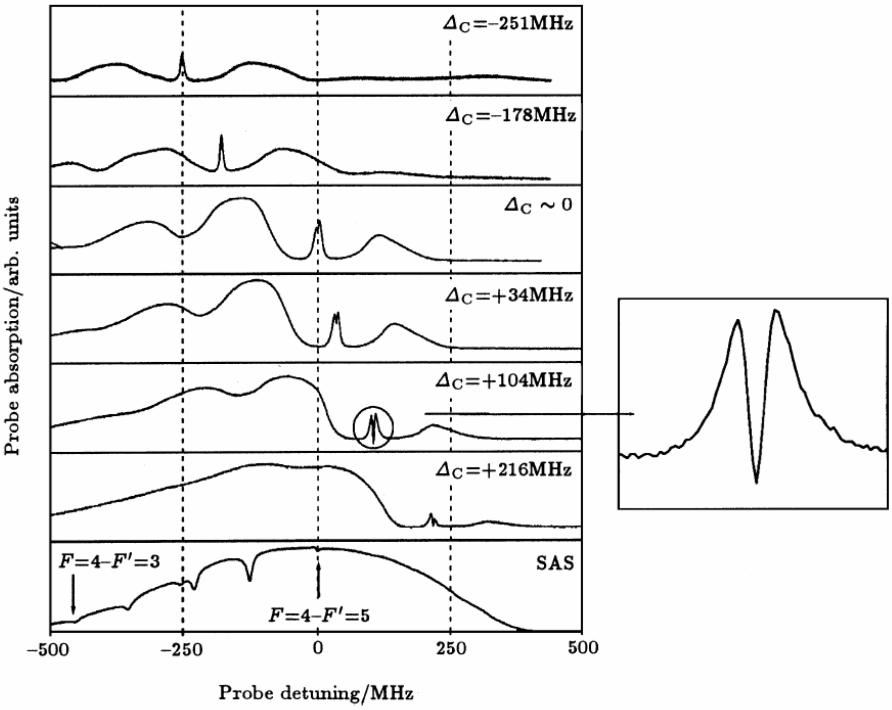

Fig.3. Pump–probe spectra of F=4–F'=3, 4, 5 transitions with different pump detuning. The cycling transition F=4–F'=5 is a reasonable choice of the reference frequency. The saturated absorption spectrum is used for frequency calibration. The absorption-enhanced peak in the case of near resonant pump laser ($\Delta_C \sim 0$) is due to EIA effect. The circle indicates an absorption reduction dip inside the EIA peak.

When the pump beam is resonant with the cycling transition (detuning $\Delta_C \sim 0$) an absorption-enhanced narrow peak (EIA peak) in a broad absorption-saturated dip appears at F=4–F'=5 closed transition (the third curve from top in Fig.3). The absorption-saturated dip can be understood with the help of a simple two-level model. In the two-level system formed by F=4 ground state and F'=5 excited state the pump beam makes absorption of the probe beam saturated. The EIA peak is expected in the theoretical analysis based on degenerate Zeeman sublevels in both ground and excited states in Refs.[10,11].

When the pump beam is tuned to F=4–F'=4 hyperfine transition (Δ_C=−251MHz) EIA peak appears at the same transition (the first curve from top in Fig.3). Here F=4–F'=4 hyperfine transition is not a closed transition. In this case, the above-mentioned second and third conditions for EIA in Ref.[5] are not fulfilled. Actually EIA is possible in open system as was pointed out in EIA theory of Refs.[10,11]. Also several similar experiments were demonstrated.[12–15] Because of the hyperfine optical pumping most of atoms are pumped to F=3 ground state, so the absorption signal as well as the EIA peak are much smaller than that in the case of F=4–F'=5 closed transition.

When the pump detuning is increased positively ($\Delta_C > 0$), an absorption-reduction dip appears inside the EIA peak (the fourth to sixth curves from top in Fig.3). The zoomed plot, at right side of Fig.3, is the typical result at the pump detuning Δ_C=+104MHz. Similar results were reported in Refs.[6,7] when the pump intensity is increased further. Taking the two-photon resonance and Raman process into account, density matrix equations were used to interpret this point and some numerical simulation results were given in Ref.[6]. But the physical reasons are still not clearly understood.

Generally an absorption-reduction EIT dip corresponds to normal dispersion, so a slow group velocity of light field is expected.[17] In recent years many experiments on slow group velocity in atomic vapour via EIT effect have been performed. In contrast, absorption-enhanced EIA peak corresponds to abnormal dispersion and faster-than-light-speed-in-vacuum group velocity of light field (superluminal light) is also expected. Here the dispersion characters of EIA peak and the sharp absorption-reduction dip inside EIA peak should be very different. Actually by utilizing these two different dispersion characters Ref.[18] presented a switch of group velocity from superluminal light via EIA to subluminal light. At least it provides an effective way to control the group velocity of light in atomic vapour.

3.2. The case of F=3–F'=2, 3 and 4 transitions

The pump–probe absorption spectra for F=3–F'=2, 3 and 4 transitions with different pump detuning are shown in Fig.4. For frequency calibration SAS

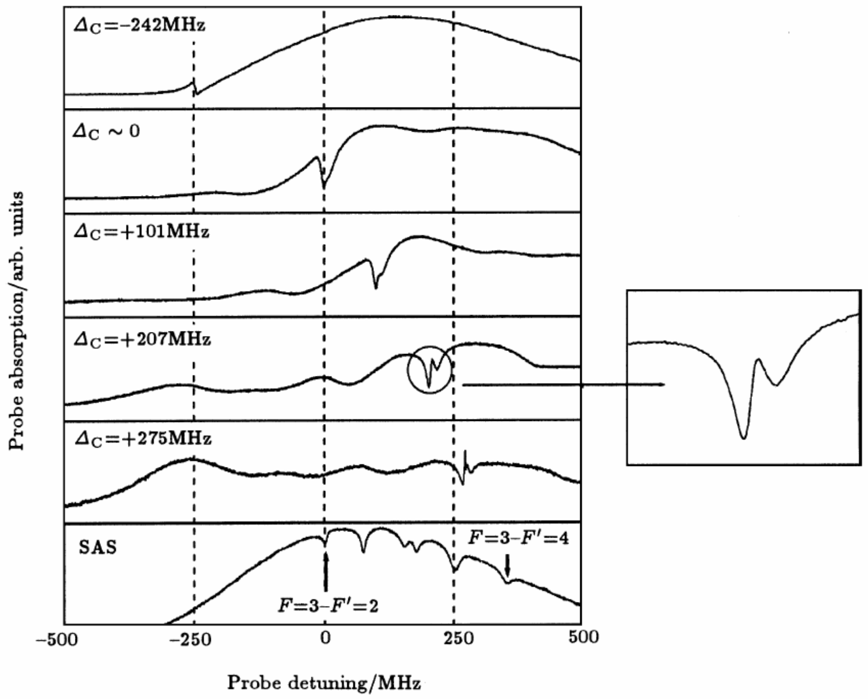

Fig.4. Pump–probe spectra of F=3–F'=2, 3, 4 transitions with different pump detuning. The saturated absorption spectrum provides a frequency calibration, and F=3–F'=2 hyperfine transition serves the reference point of pump and probe detuning. The absorption reduction dip in the case of near-resonant pump laser ($\Delta_C \sim 0$) is due to EIT effect. The circle indicates an absorption-enhanced peak inside the EIT dip.

spectrum for F=3–F'=2, 3 and 4 transitions is also given in Fig.4 (the lowest curve in Fig.4). In this case we reasonably select F=3–F'=2 cycling transition as frequency reference point. The hyperfine transition of F=3–F'=4, which is +352MHz away from the F=3–F'=2 transition, is also marked with arrowed lines in Fig.4.

When the pump beam is resonant with F=3–F'=2 transition ($\Delta_C \sim 0$) an absorption-reduction dip (EIT dip) at F=3–F'=2 transition is observed (see the second curve from top in Fig.4). When pump detuning $\Delta_C \sim$–242MHz a dispersion-like structure is demonstrated. These two cases can be understood with EIT in multi-Λ-type Zeeman sublevels in degenerate two-level system formed by F=3 ground state and F'=2 excited state.

When the pump detuning is positive ($\Delta_C > 0$), F=3–F'=2 two-level model is no longer valid because the influence of F'=3 and F'=4 excited states cannot be ignored. Maybe this is associated with the appearance of the absorption-enhanced peak inside EIT dip at Δ_C=+101MHz, +207MHz and +275MHz in Fig.4. To our knowledge, it is the first time to present the absorption-enhanced peak inside EIT dip in the case of Cs F=3–F'=2, 3 and 4 transitions, even though at this moment it is not clearly understood. To know the physical origin detailed theory should be developed. Theoretical analysis is in progress and will be published later.

Additionally, in both cases of F=4–F'=3, 4, 5 and F=3–F'=2, 3, 4 transitions, pump–probe absorption spectra all have rugged backgrounds (as in Fig.3 and Fig.4). Besides the above qualitative analysis, velocity selection mechanism may play an important role for such rugged backgrounds.

4. Conclusion

In conclusion, we have investigated the D_2 line pump–probe absorption spectra of Cs vapour by using two orthogonal linearly-polarized pump and probe laser beams. EIA peak is demonstrated in the case of F=4–F'=3, 4 and 5 transitions. EIT dip is observed in the case of F=3–F'=2, 3 and 4 transitions with different pump detuning and can be understood in multi-Λ-type Zeeman sublevels of degenerate F=3–F'=2 two-level system. In both cases abnormal sign-reversed signals inside EIA absorption-enhanced peak and EIT absorption-reduction dip are clearly observed with detuned pump beam.

Then one can manipulate the absorption spectra from normal structure to abnormal structure, as well as from normal dispersion to anomalous dispersion and superluminal to subluminal propagation, only by changing the detuning of the pump beam. This feature may has promising application in high-speed optical modulator and quantum information processing.

References

[1] Zibrov A S, Lukin M D, Nikonov D E, Hollberg L, Scully M O, Velichansky V L and Robinson H G 1995 *Phys. Rev. Lett.* **75** 1499

[2] Arimondo E 1996 *Prog. Opt.* **35** 257

[3] Boller K J, Imamoglu A and Harris S E 1991 *Phys. Rev. Lett.* **66** 2593

[4] Akulshin A M, Barreiro S and Lezama A 1998 *Phys. Rev.* A **57** 2996

[5] Lezama A, Barreiro S and Akulshin A M 1999 *Phys. Rev.* A **59** 4732

[6] Kim K, Kwon M, Park H D, Moon H S, Rawat H S, An K and Kim J B 2001 *J. Phys.* B **34** 4801

[7] Zhao Y T, Zhao J M, Xiao L T, Yin W B and Jia S T 2004 *Chin. Phys. Lett.* **21** 76

[8] Wang Y H, Yan S B, Wang J M, Liu T, Zhang T C and LI G 2004*Chinese J. Lasers* **31** 1065 (in Chinese)

[9] Akulshin A M, Cimmino A, Sidorov A I, Hannaford P and Opat G I 2003 *Phys. Rev.* A **67** 011801

[10] Taichenachev A V, Tumaikin A M and Yudin V I 2000 *Phys. Rev.* A **61** 011802

[11] Goren C, Wilson-Gordon A D, Rosenbluh M and Friedmann H 2003 *Phys. Rev.* A **67** 033807

[12] Kim S K, Moon H S, Kim K and Kim J B 2003 *Phys. Rev.* A **68** 063813

[13] Alzeta G, Cartaleva S, Dancheva Y, Andreeva Ch, Gozzini S, Botti L and Rossi A 2001 *J. Opt.* B **3** 181

[14] Ye C Y, Zibrov A S, Rostovtsev Y V and Scully M O 2003 *J. Mod. Opt.* **50** 2605

[15] Zhao J M, Zhao Y T, Huang T, Xiao L T and Jia S T 2005 *Chin. Phys.* **14** 725

[16] Liu C P, Gong S Q, Fan X J and Xu Z Z 2004 *Opt. Commun.* **231** 289

[17] Hau L V, Harris S E, Dutton Z and Behroozi C H 1999 *Nature* **397** 594

[18] Kim K, Moon H S, Lee Ch, Kim S K and Kim J B 2003 *Phys. Rev.* A **68** 013810