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Tripod 型双电磁诱导透明原子系统中压缩光的传输

李媛[1]，徐雪原[3]，张维[1]，高伟清[1]，张俊香[2]，徐进章[3]
（1 合肥工业大学 电子科学与应用物理学院，合肥 230009）
（2 山西大学 光电研究所 量子光学与光量子器件国家重点实验室，太原 030006）
（3 合肥工业大学 电气与自动化工程学院，合肥 230009）

摘　要：采用海森堡-朗之万方法理论研究了 Tripod 型双电磁诱导透明原子系统中压缩态探针场的传输特性. 研究结果表明：通过双透明窗口压缩光可实现双通道传输，且每个通道可以被独立操控；当两束耦合场的频率失谐相等时，输出探针场的压缩度可以得到更好的保持. 此外，输出探针场的压缩度可以通过耦合场的拉比频率、原子的光学厚度和基态退相干率以及探测频率来操控. 该研究结果为进一步优化多通道量子存储提供依据.

关键词：量子光学；电磁诱导透明；压缩光；量子噪声；探测频率；Tripod 型系统

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Squeezing Propagation through Double Electromagnetically Induced Transparency in a Tripod-Type Atomic System

LI Yuan[1], XU Xue-yuan[3], ZHANG Wei[1], GAO Wei-qing[1], ZHANG Jun-xiang[2], XU Jin-zhang[3]
(1 *School of Electronic Science & Applied Physics*, *He Fei University of Technology*, *Hefei* 230009, *China*)
(2 *State Key Laboratory of Quantum Optics and Quantum Optics Devices*, *Institute of Opto-electronics*, *Shanxi University*, *Taiyuan* 030006, *China*)
(3 *School of Electrical Engineering and Automation*, *Hefei University of Technology*, *Hefei* 230009, *China*)

Abstract: The squeezed probe light transmission characteristic through a double electromagnetically induced transparency in tripod-type atomic system was investigated by using the Heisenberg-Langevin approach. The results show that, the squeezing can survive in two electromagnetically induced transparency windows independently. The output squeezing in tripod-type atoms can be better preserved when the frequency detunings of two coupled fields are equal. It is found that the output squeezing is also determined by the Rabi frequency of coupling fields, optical depth and dephasing rate of atoms, and detection frequency. This study has a potential application in multi-channel quantum memory for quantum network.

Key words: Quantum optics; Electromagnetically induced transparency; Squeezed state light; Quantum noise; Detection frequency; Tripod-type system

OCIS Codes: 270.0270; 020.0020; 020.1670; 270.6570

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First author: LI Yuan (1985－), female, lecturer, Ph. D. degree, mainly focuses on quantum optics. Email: liyuan@hfut.edu.cn

Corresponding author: ZHANG Jun-xiang (1966－), female, professor, Ph. D. degree, mainly focuses on quantum optics. Email: Junxiang@sxu.edu.cn

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0 Introduction

It is well known that Electromagnetically Induced Transparency (EIT) is a quantum coherent effect with a promising approach for atomic-ensemble-based optical and quantum memory[1], which plays a crucial role for quantum information processing and quantum communication network[2]. Storage and retrieval of a squeezed vacuum via EIT effect has been experimentally realized in atomic vapor and trapped atoms[3-4]. Optical and quantum memory needs that a quantum state can reversibly transfer between an atomic ensemble and a light field, and the storage efficiency is assessed via detecting the quantum noise of the retrieved light. In the process of storage, the squeezing of a quantized field could be well preserved by the quantum coherence, e. g. in a three-level Λ-type EIT system[5], which has been studied widely and deeply. The theoretical calculations were proposed by Lam *et al*[6] and Dantan *et al*[7]. Zhang *et al* showed that the noise spectrum of delayed light for nonzero detection frequency also can be well preserved by tuning the two-photon detuning[8], which is useful in improving the quality of the experiment. Akamatsu *et al* have experimentally observed the squeezing of the delayed light pulse[9].

With the development of new features of quantum coherences in multi-level schemes, such as the Double EIT (DEIT) coherence[10] and nonlinearity with two-photon absorption and large cross-phase modulation[11-12], the storage of light was suggested in two channels[13], and the squeezing can be simultaneously preserved in four-level atomic systems[14-15]. Recently, Sanders *et al* have found coherent gain and slow light in a tripod-type EIT atomic system[16-17], which can be used to achieve matched group velocity and enhance the nonlinear interaction for optical communication. The tripod EIT configuration has been used to realize quantum memory experimentally, such as the storage of multiple images[18] and coherent manipulation of a stored single-photon wave packet[19]. In this article, we study the dependence of squeezing on the systematic parameters in light-atom coupled scheme to maximize the output squeezing degree, which is carried by the light beam propagating through DEIT in a tripod-type atomic system. It shows that the output squeezing can be better preserved via the DEIT coherence and the squeezing can propagate in two channels independently, which paves the way for the experimental implementation. Then the influence of optical depth and dephasing rate of atoms and detection frequency on output squeezing was also analyzed. The results will be useful in the experimental detection for two-channel quantum memory. The tripod configuration can be realized by interacting a π-polarized probe field with an $F_g=1\leftrightarrow F_e=0$ atomic transition, driven by a σ_+-polarized coupling field and a σ_--polarized control field, and the degeneracy of the ground-state sublevels can be removed by a magnetic field.

1 Theoretical model

The tripod-type system considered here, in Fig. 1, consists of four levels: three metastable lower levels $|1\rangle$, $|2\rangle$, $|4\rangle$ and an upper level $|3\rangle$. A weak quantum probe field $\hat{a}(z,t)$ of frequency ω_p couples the transition $|3\rangle\leftrightarrow|4\rangle$, and two classical coupling fields Ω_1, Ω_2 with frequency ω_1, ω_2 couple the transitions $|3\rangle\leftrightarrow|1\rangle$ and $|3\rangle\leftrightarrow|2\rangle$. $\delta_p=\omega_{34}-\omega_p$, $\delta_1=\omega_{31}-\omega_1$ and $\delta_2=\omega_{32}-\omega_2$ are the detunings of the three fields, where $\omega_{\mu\nu}$ is the atomic transition frequency of $|\mu\rangle\leftrightarrow|\nu\rangle$. In the rotating frame, with the rotating-wave and dipole approximation, the Hamiltonian of this system is

$$\hat{H}=h(\delta_2-\delta_1)|1\rangle\langle1|+h\delta_2|3\rangle\langle3|+h(\delta_2-\delta_p)|4\rangle\cdot\langle4|-h\Omega_1(|3\rangle\langle1|+|1\rangle\langle3|)-h\Omega_2(|3\rangle\langle2|+|2\rangle\langle3|)-h(g\hat{a}|3\rangle\langle4|+g^*\hat{a}^+|4\rangle\langle3|) \tag{1}$$

where $2\Omega_1$, $2\Omega_2$ are the Rabi frequencies of the two coupling fields, and g is the coupling constant between the atomic transition $|3\rangle\leftrightarrow|4\rangle$ and the quantized mode $\hat{a}$.

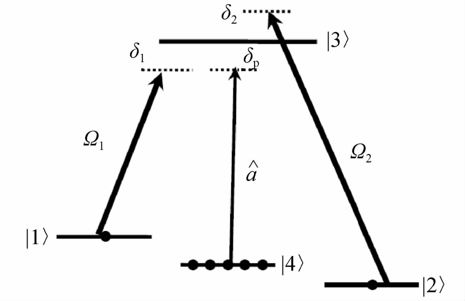


Fig. 1 Schematic of a tripod-type system

Assuming that the quantized probe is much less than the two couplings and all the atoms are initially in the lower level $|4\rangle$ with $\langle\sigma_{44}\rangle\approx1$, the evolution equations for both the atomic operators and the annihilation operator of the probe are given by

$$\begin{cases}\dot{\hat{\sigma}}_{41}=-[\mathrm{i}(\delta_p-\delta_1)+\gamma_{14}]\hat{\sigma}_{41}+\mathrm{i}\Omega_1\hat{\sigma}_{43}+\hat{F}_{41}\\ \dot{\hat{\sigma}}_{42}=[\mathrm{i}(\delta_2-\delta_p)-\gamma_{24}]\hat{\sigma}_{42}+\mathrm{i}\Omega_2\hat{\sigma}_{43}+\hat{F}_{42}\\ \dot{\hat{\sigma}}_{43}=-(\mathrm{i}\delta_p+\gamma_{34})\hat{\sigma}_{43}+\mathrm{i}\Omega_1\hat{\sigma}_{41}+\mathrm{i}\Omega_2\hat{\sigma}_{42}+\mathrm{i}g\hat{a}+\hat{F}_{43}\\ \left(\dfrac{\partial}{\partial t}+c\dfrac{\partial}{\partial z}\right)\hat{a}(z,t)=\mathrm{i}g^*N\hat{\sigma}_{43}(z,t)\end{cases} \tag{2}$$

where $\hat{F}_{\mu\nu}$ is the associated Langevin noise operators which describe the effect of spontaneous decay caused by the coupling of atoms to all the vacuum field modes and N is the number of atoms. γ_{34} is the decay rate of the atomic dipole operator $\hat{\sigma}_{43}$. γ_{14} and γ_{24} are the dephasing rates between the lower levels caused by atomic collisions and atomic transit outside the interaction region.

Using the Fourier transform, we convert the Eq. (2) into ones in the frequency domain. Then the annihilation operator of the probe at the exit of the EIT medium with the length L is

$$\hat{a}(L,\omega)=\hat{a}(0,\omega)\exp\left[-\Lambda(\omega)L\right]-\frac{g^{*}N}{c}\cdot \int_{0}^{L}\hat{F}(s,\omega)\exp\left[-\Lambda(\omega)(L-s)\right]\mathrm{d}s \qquad (3)$$

where $\Lambda(\omega)=\frac{|g|^{2}N}{c}\times\frac{r_b r_c}{Z(\omega)}-\frac{\mathrm{i}\omega}{c}$ and $\hat{F}(s,\omega)=\frac{-\Omega_1 r_b\hat{F}_{41}(s,\omega)-\Omega_2 r_c\hat{F}_{42}(s,\omega)+\mathrm{i}r_b r_c\hat{F}_{43}(s,\omega)}{Z(\omega)}$, with $r_a=\gamma_{34}+\mathrm{i}(\delta_{\mathrm{p}}-\omega)$, $r_b=\gamma_{24}+\mathrm{i}(\delta_{\mathrm{p}}-\delta_2-\omega)$, $r_c=\gamma_{14}+\mathrm{i}(\delta_{\mathrm{p}}-\delta_1-\omega)$, $Z(\omega)=r_a r_b r_c+r_b\Omega_1^2+r_c\Omega_2^2$ and ω is the detection frequency in experiments.

By using the generalized Einstein relation in quantum regression theorem, the correlation functions of Langevin noise operators can be calculated[6, 20] and the nonzero terms are as follows

$$\begin{cases}\langle\hat{F}_{41}(s,\omega)\hat{F}_{41}^{+}(s',-\omega')\rangle=2\gamma_{14}L\delta(s-s')\delta(\omega-\omega')/N\\ \langle\hat{F}_{42}(s,\omega)\hat{F}_{42}^{+}(s',-\omega')\rangle=2\gamma_{24}L\delta(s-s')\delta(\omega-\omega')/N\\ \langle\hat{F}_{43}(s,\omega)\hat{F}_{43}^{+}(s',-\omega')\rangle=2\gamma_{34}L\delta(s-s')\delta(\omega-\omega')/N\end{cases} \qquad (4)$$

According to the definition of amplitude and phase quadratures of the probe light and the quadrature flux spectrum[8], the amplitude noise spectrum of the output probe reads

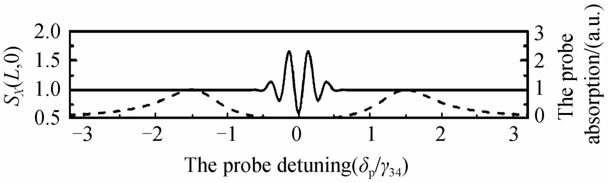
$$\begin{aligned}S_X(L,\omega)=&\{[S_X(0,\omega)/4][\exp(-[\Lambda(\omega)+\Lambda(-\omega)]L)+\\&\exp(-[\Lambda(\omega)+\Lambda^{*}(\omega)]L)+\exp(-[\Lambda^{*}(-\omega)+\\&\Lambda(-\omega)]L)+\exp(-[\Lambda^{*}(-\omega)+\Lambda^{*}(\omega)]L)]\}-\\&\{[S_Y(0,\omega)/4][\exp(-[\Lambda(\omega)+\Lambda(-\omega)]L)-\\&\exp(-[\Lambda(\omega)+\Lambda^{*}(\omega)]L)-\exp(-[\Lambda^{*}(-\omega)+\\&\Lambda(-\omega)]L)+\exp(-[\Lambda^{*}(-\omega)+\Lambda^{*}(\omega)]L)]\}+\\&(D_{\mathrm{opt}}/2\gamma_{34})\times[1-\exp(-[\Lambda(\omega)+\Lambda^{*}(\omega)]L)]/\\&([\Lambda(\omega)+\Lambda^{*}(\omega)]L)\times[2\gamma_{14}|r_b|^2\Omega_1^2+2\gamma_{24}\cdot\\&|r_c|^2\Omega_2^2+2\gamma_{34}|r_b r_c|^2]/|Z(\omega)|^2\end{aligned} \qquad (5)$$

where $D_{\mathrm{opt}}\equiv 2|g|^2NL/c\gamma_{34}$ is the Optical Depth (OD) of atomic ensemble [5].

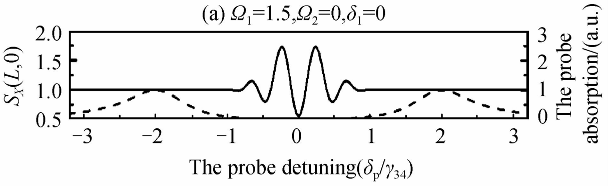
The output amplitude noise expressed by Eq. (5) has three sources, i. e., the three terms on the right-hand side. The first term is related to amplitude noise of the input probe light $S_X(0,\omega)$; the second term is related to phase noise of the input probe light $S_Y(0,\omega)$, which contributes to the output amplitude noise due to the phase-to-amplitude noise conversion; the last term arises from environment bath caused by the coupling of atoms to all the vacuum field modes.

2 Results and discussion

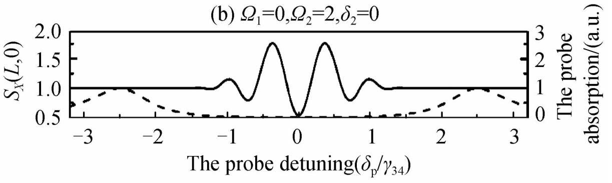
In the following discussion, we assume that the input probe is a 3 dB amplitude-squeezed state i. e. $S_X(0,\omega)=0.5$, $S_Y(0,\omega)=2$, with 1.0 is the Shot Noise Level (SNL), $D_{\mathrm{opt}}=50$, $\gamma_{14}=\gamma_{24}=0.01$, $\gamma_{34}=1$. Firstly, we consider the three-level Λ-type system driving by only one coupling field, as shown in Fig. 2(a), the output noise is 0.6, which is lower than SNL, showing that the squeezing is preserved at the transparency point under the condition of ground-state dephasing rate[8]. Similarly, in Fig. 2(b), when only the coupling 2 is applied, 0.56 output noise means that the squeezing is also preserved[5]. With both the two couplings, $\Omega_1=1.5$, $\Omega_2=2$, $\delta_1=\delta_2=0$, there will be two degenerate dark states, as shown in Fig. 2(c), an enhanced transparency window emerges, and the preserved squeezing with lower output noise 0.54 is obtained. When the detunings of couplings are unequal, the two dark states are nondegenerate. The squeezing propagates simultaneously in two transparency windows shown in Fig. 2(d).



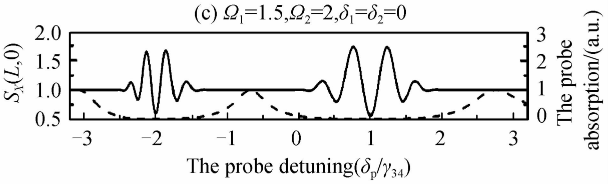
(a) Ω_1=1.5,Ω_2=0,δ_1=0



(b) Ω_1=0,Ω_2=2,δ_2=0



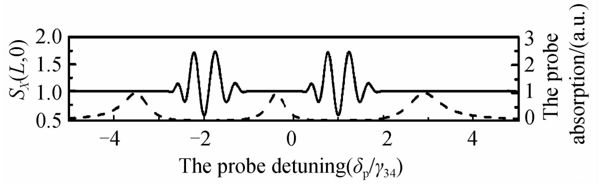
(c) Ω_1=1.5,Ω_2=2,δ_1=δ_2=0



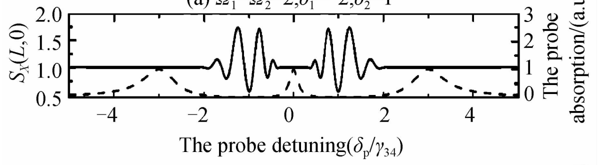
(d) Ω_1=1.5,Ω_2=2,δ_1=−2,δ_2=1

Fig. 2 Output amplitude noise $S_X(L,\omega=0)$ and absorption versus probe detuning

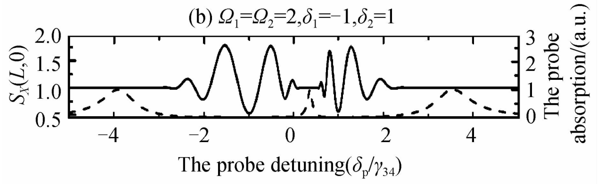
To further demonstrate the squeezing features in the two channels, the effects of strength and detuning of couplings are shown in Fig. 3. When the detuning of coupling 1 decreases, the left channel is close to the right one which remains unchanged, shown in Fig. 3(a) and Fig. 3(b). When the Rabi frequency of coupling 1 increases, the squeezing of the left channel increases and the right channel still remains unchanged, shown in Fig. 3 (c). When the detuning and strength of coupling 2 vary, the left channel remains unchanged shown in Fig. 3(d). We can see clearly that squeezing can propagate in two channels independently, and each channel can be manipulated by setting its parameters without affecting the other one.



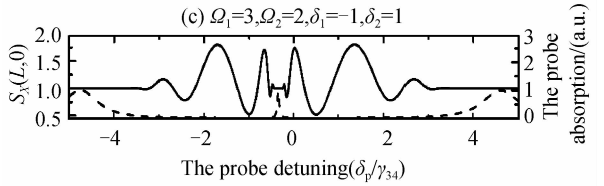
(a) $\Omega_1=\Omega_2=2,\delta_1=-2,\delta_2=1$



(b) $\Omega_1=\Omega_2=2,\delta_1=-1,\delta_2=1$



(c) $\Omega_1=3,\Omega_2=2,\delta_1=-1,\delta_2=1$



(d) $\Omega_1=3,\Omega_2=3.5,\delta_1=-1,\delta_2=0.5$

Fig. 3 Output amplitude noise $S_X(L,\omega=0)$ and absorption versus probe detuning

Besides the coupling strength, the OD of atomic ensemble has a strong influence on the squeezing feature, as shown in Fig. 4, where $\Omega_1=2, \Omega_2=1.5, \delta_1=-1, \delta_2=2$. The squeezing can be well preserved at an optically thin medium. With the increase of OD, the atomic noise is caused by vacuum field modes and the oscillatory transfer between amplitude noise and phase noise increase. This result can be illustrated by the Eqs. (4) and (7), which is similar to that in Λ-type system[5].

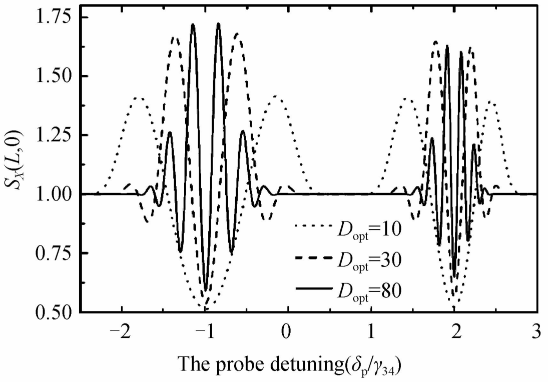
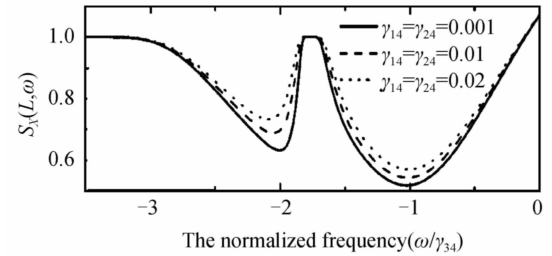
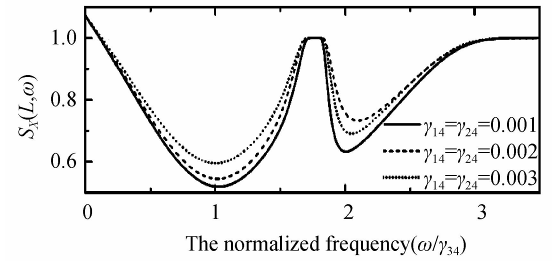


Fig. 4 Output amplitude noise versus probe detuning for different ODs

Due to the relaxation oscillation of lasers, the squeezing can not be detected at zero frequency under realistic experiments. Assuming $\Omega_1=3, \Omega_2=1.5, \delta_p=0$, $D_{opt}=50, \gamma_{34}=1$. Fig. 5 shows that the squeezing can be simultaneously detected at two positive or negative frequencies $\omega\approx-\delta_{1,2}$ by setting the two-photon detuning [8], which is equal to the detuning of coupling with the probe is under the one-photon resonance condition ($\delta_p=0$) here. And the maximum squeezing is also limited by the dephasing rates. As shown in Ref. [15], the squeezing can be detected at a positive and a negative frequency, where the system is drived by two coupling fields with the same Rabi frequency.



(a) $\delta_1=1,\delta_2=2$



(b) $\delta_1=-1,\delta_2=-2$

Fig. 5 Output amplitude noise $S_X(L,\omega)$ versus detection frequency for different dephasing rates

3 Conclusion

We demonstrated the propagation of a squeezed state light through the DEIT in a tripod-type atomic system, showing the dependence of the strength and detuning of coupling fields, OD of atomic ensemble and dephasing rate on the output squeezing. It is also shown that the output squeezing can be controlled at two positive or negative frequencies with different values. This discuss is useful for improving the experimental realization of multi-channel quantum memory in quantum communication network.

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