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VIPA-based two-component detection for a coherent population trapping experiment

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We demonstrate a two-component detection of a coherent population trapping (CPT) resonance based on virtually imaged phased array (VIPA). After passing through a VIPA, the two coupling lights with different frequencies in the CPT experiment are separated in space and detected individually. The asymmetric lineshape is observed experimentally in the CPT signal for each component, and the comparison with the conventional detection is presented. The shift of the CPT resonant frequency is studied with both the two-component and one-component detections. Our scheme provides a convenient way to further study the CPT phenomenon for each frequency component.

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1. Introduction

Coherent population trapping (CPT) is one of the most famous phenomena in quantum optics and provides an excellent example for showing quantum nature. It has been observed since 1976^[1-3] and has been realized in various systems, such as thermal atoms in a vapor cell^[1,4], cold atoms^[5,6], and nitrogenvacancy centers in diamond^[7]. When the frequency difference between the two coupling lights matches the atomic hyperfine transition, less absorption appears. This CPT signal enables us to refer the microwave frequency to the clock transition of atoms and realize a CPT clock^[8,9]. Such a clock has the advantages of being compact and low cost and has attracted lots of attention^[10–13].

The simplest CPT structure involves three energy levels, as shown in Fig. 1(a), which is called the Λ -type structure. The two coupling lights are associated with the frequencies of ω_1 and ω_2 , respectively, and the Rabi frequencies are Ω_{ab} and Ω_{ac} accordingly. They couple three levels of $|a\rangle$, $|b\rangle$, and $|c\rangle$. Δ is the single-photon detuning, and δ_0 is the two-photon detuning. When $\delta_0 = 0$, the CPT state is created, and less absorption happens at this point. The three-level model is very simple and captures the main physics, which we use as the main model for theoretic simulations. In the real experiments, of course, more hyperfine and Zeeman states are involved. Figure 1(b) shows the energy levels involved in our experiment with the D1 transition of ⁸⁷Rb. Two σ^+ lasers are used to couple the hyperfine states $|F = 1, m_E = m\rangle$ and $|F = 2, m_E = m\rangle$ $(m = 0, \pm 1)^{[9]}$. The single-photon detuning Δ and two-photon detuning δ_0 in the experiment are defined, as shown in the Fig. 1(b).

Most CPT experiments detect the CPT signals with lights including both ω_1 and ω_2 frequency components, which we call one-component detection, and this total CPT signal is labelled as I_{total} . It is easy and straightforward to detect the total CPT signal, and it gives better frequency stability for the CPT clock compared with the single-frequency component detection. Few experiments tried to extract the information about the individual frequency component by either the heterodyne-detected method^[14] or with different polarization^[15]. Such



Fig. 1. A-type energy structure of the CPT experiment. (a) The simple three-level model. (b) The energy levels involved in the real experiment. The main transitions are the D1 transitions of 87 Rb.

two-component detections give more information about the CPT phenomenon, but with a more complex experimental setup or the need to change the polarizations of coupling lights. A convenient and undisturbed way to separate the two coupling lights for CPT detection is still desired.

Usually, the frequency difference between two coupling lights is in the gigahertz (GHz) regime (such as 6.8 GHz for Rb atom and 9.2 GHz for Cs atom). Even for a high resolution grating, it is hard to separate the coupling lights with such a high spectrum resolution. On the other hand, the virtually imaged phased array (VIPA), which is a rectangle etalon, provides a good solution to separate lights with such a frequency difference. It has been widely used for molecular spectroscopy^[16,17] or Brillouin spectroscopy^[18,19] with frequency difference in the GHz regime. It also finds important applications in the frequency comb experiments, helping to get massive and high resolution spectroscopy at the same time^[20,21]. Here, we develop a novel two-component detection of the CPT experiment based on a VIPA. It has the advantage of high spectrum resolution and no need to change the polarizations of the coupling lights.

2. Experimental Setup

The experimental setup is shown in Fig. 2. Figure 2(a) is the same as most conventional CPT experiments^[22–25]. A vertical cavity surface emitting laser (VCSEL) is used as the light source and is locked to the D1 transition (F = 2 to F' = 1) of Rb atoms through the dichroic atomic vapor laser lock (DAVLL)^[26]. It is modulated by a microwave with a frequency of $\omega_m \simeq 6.8$ GHz. The microwave is referred to as a Rb atomic clock (model FS725, Stanford Research System). The zero order of the laser is near resonance with the F = 2 to F' = 1 transition, and the +1 order is near resonance with the F = 1 to F' = 1 transition. The $\{0, +1\}$ orders form one pair of CPT lights near resonance. The $\{0, -1\}$ orders can form another pair of CPT light but with the single-photon detuning at $\Delta \simeq 6.8$ GHz and can be ignored in the current study. In order to change Δ , the laser double passes an acoustic-optical modulator (AOM) as shown in Fig. 2(a). It then passes a Rb buffer-gas quartz cell, which is inside a three-layer magnetic shielded box with a residual magnetic field of 10 nT. A bias magnetic field can be created by the solenoid to define the quantization axis ($< 0.1 \,\mu\text{T}$ in our case). The laser power is about 60 μ W, and the beam diameter is about 0.5 mm. The cell is 20 mm in diameter and 21 mm long. The temperature of the cell is maintained at about 53°C. The buffer gases are argon and nitrogen with the pressure ratio of 1.6:1, and the total pressure is about 2.8×10^3 Pa. After the cell, the laser is coupled into a fiber.

The main difference of our scheme, compared with traditional CPT scheme, is shown in Fig. 2(b). The laser coming out of the fiber is sent into a VIPA^[27]. The VIPA we used is from LightMachinery company model OP-6721-6743-4, with a free spectral range of 15 GHz. The laser is focused by a cylindrical lens before entering the VIPA. After passing the VIPA, the laser is refocused by the cylindrical lenses in two directions. So, lights



Fig. 2. Experimental setup. (a) The main part of the CPT experiment. In order to change the single-photon detuning, the laser double passes an AOM before entering the Rb buffer-gas cell. After the cell, the laser is coupled into a fiber. (b) The detection part of our experiment. Lights with different frequencies are spatially separated by a VIPA. The pictures show the spatial distribution of lights. Three detectors are set to measure l_1 , l_2 , and l_{total} , respectively. PBS, polarization beam splitter; BS, beam splitter; PD, photodetector; DAVLL, dichroic atomic vapor laser lock; VCSEL, vertical cavity surface emitting laser; VIPA, virtually imaged phased array; AOM, acoustic-optical modulator.

with different frequency components become spatially separated dots, as shown in Fig. 2(b). A beam splitter (BS) is used to divide the laser into two beams, and the apertures are used to pick up the lights with the desired frequency components. In our case, because the free spectrum range of the VIPA is 15 GHz, which is close to two times of 6.8 GHz, the +1 and -1 orders are very close in space and are detected together. As mentioned previously, the -1 order can be ignored in the CPT signal, because it only rises the bias of the detected signal and does not affect our results. Three detectors are set up for detection, one is for the zero order (photodetector, PD1, I_1), one is for the first order (PD2, I_2), and the third one detects light without separating ω_1 and ω_2 (PD-total, I_{total}). The center frequencies are determined from the peaks of the CPT signals, and we label them as f_1, f_2 , and f_{total} , respectively. We also define a parameter $f_{\text{ave}} = (f_1 + f_1) + f_2 + f_3 + f_3 + f_4 +$ $f_2)/2$ as the average value of f_1 and f_2 .

3. Simulations with a Three-Level Model

We first present some numerical results with the simple three-level model^[9]. The system can be described by the master equation,

$$\dot{\rho} = -\frac{i}{\hbar} [H,\rho] + \sum_{i,j} \left(C_{i,j} \rho C_{i,j}^{\dagger} - \frac{1}{2} \{ C_{i,j}^{\dagger} C_{i,j},\rho \} \right). \tag{1}$$

i, *j* represent the energy levels in Fig. 1(a). The Hamiltonian of the three-level model is

$$H = \hbar \begin{pmatrix} 0 & \Omega_{ab} & \Omega_{ac} \\ \Omega_{ab} & \Delta & 0 \\ \Omega_{ca} & 0 & \Delta - \delta_0 \end{pmatrix},$$
(2)

where $\Delta = \omega_1 - \omega_{ab}$ is the single-photon detuning, and $\delta_0 = \omega_1 - \omega_2 - \omega_{cb}$ is the two-photon detuning. The collapse operator is $C_{i,j} = \sqrt{\Gamma_{i,j}} |i\rangle \langle j|$. Here, we list all of the non-zero terms:

$$C_{b,a} = \sqrt{\frac{\Gamma}{2}} |b\rangle \langle a|, \qquad C_{c,a} = \sqrt{\frac{\Gamma}{2}} |c\rangle \langle a|,$$

$$C_{b,b} = \sqrt{\gamma_2 - \frac{\gamma_1}{2}} |b\rangle \langle b|, \qquad C_{c,c} = \sqrt{\gamma_2 - \frac{\gamma_1}{2}} |c\rangle \langle c|,$$

$$C_{b,c} = \sqrt{\frac{\gamma_1}{2}} |b\rangle \langle c|, \qquad C_{c,b} = \sqrt{\frac{\gamma_1}{2}} |c\rangle \langle b|. \qquad (3)$$

The simulation parameters are chosen to be the decay rate of the excited state $\Gamma/2\pi = 2000$ MHz, which is mainly due to collision with buffer gas, the relax rate of the populations of the two lower states $\gamma_1/2\pi = 1000$ Hz, and the relax rate of the coherence between two lower states $\gamma_2/2\pi = 5000$ Hz, and we change the Rabi frequencies and the detuning. Figure 3(a) shows the theoretical CPT lineshapes versus the two-photon detuning δ_0 with the single-photon detuning $\Delta/2\pi = -300$ MHz, $\Omega_{ab} =$ 0.002 Γ , and $\Omega_{ac} = 0.001\Gamma$ for I_1, I_2 , and I_{total} . Although the single-photon detuning is not zero, I_{total} is still quite symmetric with δ_0 . But, I_1 and I_2 show strong asymmetry, and the center frequencies are shifted away from $\delta_0 = 0$ with opposite directions. But, I_{total} , which can be considered as the sum of I_1 and I_2 , becomes more symmetric, and the center frequency is much closer to $\delta_0 = 0$. That is part of the reason why I_{total} is used to realize the CPT clock. Figures 3(b)-3(d) show the numerical results of how f_1, f_2, f_{ave} , and f_{total} vary as we change Δ when $\Omega_{ab} = \Omega_{ac} = 0.001\Gamma; \qquad \Omega_{ab} = 0.001\Gamma, \Omega_{ac} = 0.0015\Gamma;$ $\Omega_{ab} =$ 0.002 Γ , $\Omega_{ac} = 0.001\Gamma$. In Fig. 3(b), we can clearly see that both f_{total} and f_{ave} are insensitive with Δ when $\Omega_{ab} = \Omega_{ac}$. One can think that, because the intensity is balanced, the weights of I_1 and I_2 to I_{total} are the same, so f_{total} and f_{ave} show similar behaviors. But when $\Omega_{ab} \neq \Omega_{ac}$, the weights are not the same for the two components, so the center frequencies show different behaviors, as shown in Figs. 3(c) and 3(d). Though f_1 and f_2 change a lot when Δ changes, f_{ave} remains stable for a wide range of Δ and $\Omega_{ab}/\Omega_{ac}\!,$ while $f_{\rm total}$ has larger variations when $\Omega_{ab} \neq \Omega_{ac}$. The numerical simulations with three-level model show that the frequency stability of f_{ave} is better than f_{total} when the Rabi frequencies and the single-photon detuning change in certain regimes.



Fig. 3. Numerical results with the simple three-level model. The simulation parameters are $\Gamma/2\pi = 2000$ MHz, $\gamma_1/2\pi = 1000$ Hz, and $\gamma_2/2\pi = 5000$ Hz. (a) Typical CPT signals for h_1 , h_2 , and h_{otal} when $\Delta/2\pi = -300$ MHz, $\Omega_{ab} = 0.002\Gamma$, $\Omega_{ac} = 0.001\Gamma$. They are shifted vertically for a better visibility. (b)-(d) The center frequencies versus Δ when Ω_{ab}/Ω_{ac} equals (b) 1:1, (c) 1:1.5, and (d) 2:1. The results show that f_{ave} is insensitive against the change of Δ and Ω_{ab}/Ω_{ac} .

4. Experimental Results

The numerical findings are verified by experiments with the new detection scheme based on a VIPA. The experimental data are shown in Fig. 4. One typical CPT signal is shown in Fig. 4(a) when $\Delta/2\pi = -190$ MHz and $\Omega_{ab}/\Omega_{ac} = 1:0.55$. The signals of I_1 and I_2 show strong asymmetry, and I_{total} is more symmetric, as predicted with the theoretic simulations. The center frequencies are extracted from the peaks of the CPT signals.



Fig. 4. Experimental data. (a) Typical CPT signals for l_l , l_2 , and l_{total} versus δ_0 when $\Delta/2\pi = -190$ MHz and $\Omega_{ab}/\Omega_{ac} = 1:0.55$. They are shifted vertically for better visibility. Both l_1 and l_2 show strong asymmetry, while l_{total} is more symmetric. (b) The center frequencies versus Δ . Both f_1 and f_2 are very sensitive to Δ , but f_{ave} is insensitive to Δ . The slope of f_{ave} is smaller than that of f_{total} .



Fig. 5. Numerical results with the four-level model. The simulation parameters are $\Gamma/2\pi = 2000$ MHz, $\gamma_1/2\pi = 1000$ Hz, and $\gamma_2/2\pi = 5000$ Hz. $\Omega_{ab}/\Omega_{ac} = 1.0.55$.

Figure 4(b) presents the center frequencies versus Δ . Each point contains three sets of data, and each set of data is averaged 4000 times. We fit the data in Fig. 4(b) with a linear function. The slope of f_{total} is smaller than that of f_1 and f_2 , but larger than that of f_{ave} . This result is consistent with the ion from the three-level model. For real Rb atoms, more energy levels need to be considered. One can think that the real energy levels can be decomposed with multiple three-level sets. For each set, f_{total} is more sensitive to Δ than f_{ave} . When multiple sets work together, f_{total} will be more sensitive to Δ than f_{ave} .

In order to understand the results better, we perform a numerical simulation with a four-level model in Fig. 1(b) (here we ignore the Zeeman substates). Figure 5 shows the numerical results of a four-level CPT system. This simulation reflects the effect of the two upper levels of the Rb D1 transition (F' = 1, F' = 2) on the CPT signal. With the ground states, the two upper levels produce two sets of three-level systems and have opposite effects on the shift of the signal. Thus, we will find a cross of these lines between the two upper levels, where the single-photon detuning is not zero. The four-level model simulation confirms that f_{total} is more sensitive to $\Delta \tanh f_{\text{ave}}$, but still has some deviations compared with the experimental data quantitatively. The attenuation of light in the media, the Zeeman sublevels, and the -1 order sideband of the modulated laser need to be considered for more precise numerical simulations^[9].

5. Conclusion

We have demonstrated a two-component detection for the CPT experiment based on a VIPA. This detection allows us to study the asymmetric lineshapes with more detailed information. For example, with such a detection scheme, we could search the parameter regime where the averaged center frequency of the CPT signals is more insensitive to experimental parameters, such as the single-photon detuning and Rabi frequencies, than the total center frequency. It might be useful for building new CPT clocks with better frequency stability.

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