Constructive, Destructive and Differential Detection of Coherent Population Trapping Resonance

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***Summary*— We propose and demonstrate constructive, destructive and differential detection of coherent population trapping resonance (CDD CPT), in which a CPT dark state is constructively and destructively detected by a bi-chromatic light field with proper polarization and timing setting. Electromagnetically induced transparency (EIT) and electromagnetically induced absorption (EIA) resonances are simultaneously observed in a vapor cell. A differential-CPT (diff-CPT) signal, with doubled amplitude and suppression of common-mode noise of light and of the atomic ensemble, is then obtained by subtracting EIT and EIA resonances. This approach might be of great interest for the development of high-performance atomic clocks, sensors, or high-resolution spectroscopy.**

Keywords*— *coherent population trapping (CPT); electromagnetically induced transparency (EIT); electromagnetically induced absorption (EIA); differential detection

I. Introduction

Coherent population trapping (CPT) [1] is a quantum interference process that consists of making atoms interact with a dual-frequency field that connects two ground states of the atomic ensemble to a common excited state. At null Raman detuning, atoms are pumped in a so-called dark state in which electromagnetically-induced transparency (EIT) of the atomic medium is obtained.

The opposite behavior, increased absorption, can be obtained with electromagnetically-induced absorption (EIA) [2]. The latter can be observed in 3-level Λ-schemes with properly-tuned counterpropagating bi-chromatic fields such that a dark state created by a dual-frequency field is a bright state for the second field.

Best CPT clocks exhibit short-term fractional frequency stability levels in the range of a few 10^{-13} at 1 s [3-5]. In [6], an EIA clock was demonstrated with a short-term stability of $4x10^{-12}$ at 1 s.

While the short-term stability of CPT clocks is comparable to one of the best microwave vapor cell clocks [7], it remains about a factor 10 higher than the ultimate photon shot noise limit. When ultra-low noise local oscillators are used [8] such that the Dick effect contribution is well rejected, the short-term stability of high-performance CPT clocks is in generally limited by the laser noise, especially the laser amplitude noise.

In this study, we propose and demonstrate a method of coherent population trapping resonances in an atomic vapor based on the simultaneous detection of mirror-images of transmission (dark state-EIT) and absorption resonances (bright state-EIA) for the clock transition, and subsequent use of a differential detection stage at the cell output [9, 10]. This technique leads to the detection of an atomic resonance with enhanced amplitude and suppressed common noise.

II. Experimental setup

Figure 1 shows a simplified scheme of the experimental setup implemented for demonstration of the proposed method.

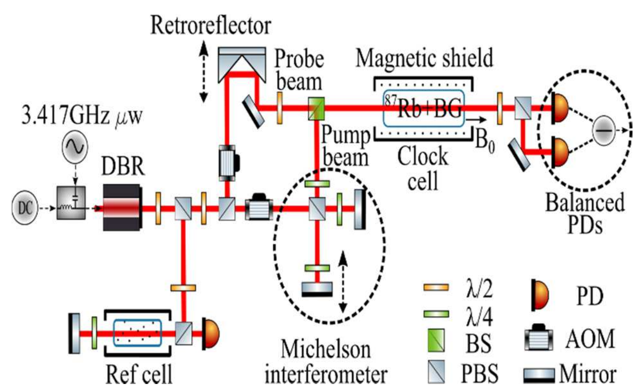

Fig. 1: Experimental setup.

The laser source is a distributed Bragg-resonator (DBR) laser, tuned on the Rb D_1 line, directly-modulated at 3.417 GHz for producing optical sidebands frequency-split at 6.8 GHz for CPT interaction. The laser frequency is stabilized using the dual-frequency sub-Doppler spectroscopy [11] on an evacuated vapor cell. Initially prepared atomic ensemble into a CPT state by a pump light in the push-pull optical pumping scheme [12] created with a Michelson-like system, atoms are then probed with a phase-delayed linearly polarized bichromatic probe beam, such that the initial CPT state is a dark state or bright state for respective orthogonal circularly polarized components of the probe field. EIT and EIA resonances are then simultaneously generated due to the fact that one of the electric dipole moments of the double-Λ system is of opposite sign to the three other ones.

The ^{87}Rb isotope enriched cylindrical vapor cell (diameter: 20 mm, length: 50 mm) is filled with a mixture of buffer gases, Ar and N_2 in the pressure ratio 1.5 : 1, with a total pressure of 25 Torr. The cell temperature is stabilized to ~54.6 ºC, and surrounded by a static magnetic field and protected by a magnetic shield. Unless otherwise specified, a uniform magnetic field of B_0 = 14.6 μT is applied along the direction of the cell axis by means of a solenoid to remove the Zeeman degeneracy. At the cell output, opposite polarizations are separated and balanced photodiodes are used to obtain the output diff-CPT signal.

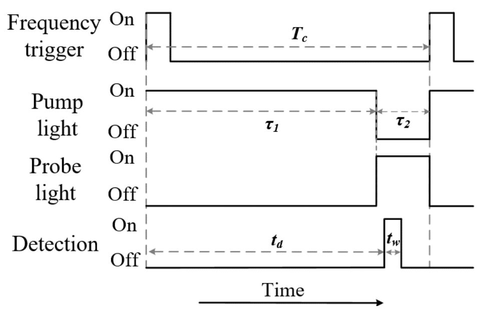

Fig. 2: The time sequence for CPT spectroscopy.

The pump-and-probe light beams, both with beam diameter around 5 mm, interrogate the atomic ensemble with the time sequence shown in Fig. 2. T_c is the cycle time. $\tau_{1(2)}$ is the pump (probe) pulse duration. The PD signals are recorded during a window of length t_w with a delay t_d after the start of a new cycle. We carry out the constructive, destructive and differential detection of coherent population trapping (henceforth we denote it as CDD CPT) on the PDs or their output difference, respectively. When a Ramsey CPT is implemented, a no light duration T (also known as Ramsey time) is inserted between the pump and probe pulse.

III. CDD CPT SPECTROSCOPY

Figure 3 shows an example of EIT, EIA and diff-CPT signals detected in the vapor cell with B_0 set as 0.87 μT.

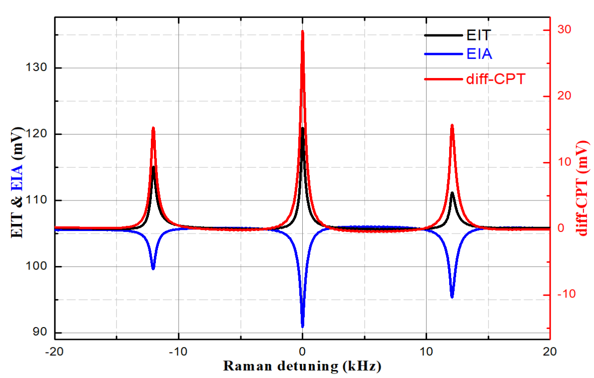

Fig. 3. Typical EIT, EIA and differential-CPT signals detected in the buffer-gas filled Rb vapor cell.

The three peaks correspond to transitions of the Zeeman spectrum, the central one being the 0-0 clock transition. The diff-CPT signal exhibits an amplitude twice higher than those of respective EIT and EIA signals, and is detected with a dc background level that is almost nulled. The linewidth of the diff-CPT signal is between those of EIT and EIA resonances. Also, we have observed common-mode noise rejection onto the diff-CPT signal. Also, we have observed common-mode noise rejection onto the diff-CPT signal as demonstrated in [10].

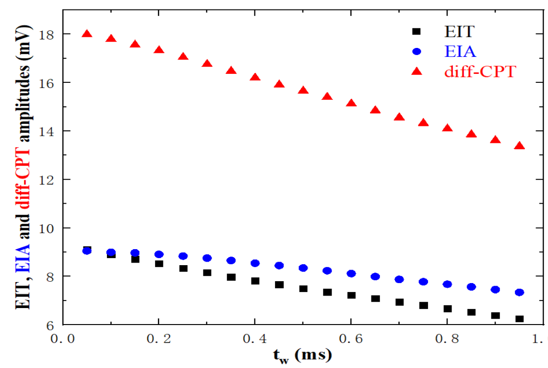

Fig. 4: EIT, EIA and differential-CPT signal amplitude of clocktransition as function of probe during window length tw, the experimental parameters are: τ1=4.5 ms, td=4.502 ms, Ppump=71 μW, Pprobe=48 μW.

We study the amplitude of clock transition of the three signals verses the probe during window length t_w, which are plotted in Fig. 4. The CPT amplitude of diff-CPT signal is only decrease about 1/3 after 1 ms of t_w with pump (probe) power P_{pump}=71 μW (P_{probe}=48 μW). The simultaneous EIT and EIA, or dark and bright states, will live together for some time. It is worth to investigate their interaction and evolution in further study.

IV. RAMSEY CDD CPT SPECTROSCOPY

Our CDD CPT spectrum scheme is compatible with Ramsey's method of separated oscillating fields in time domain, i.e., just insert a no light duration of T just following the pump time end, we can observe the Ramsey fringes of EIT, EIA and diff-CPT, see Fig. 5.

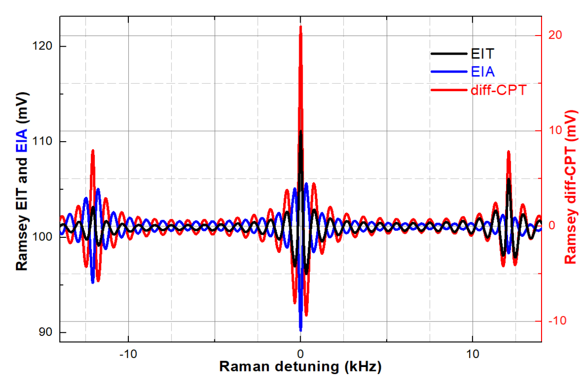

Fig. 5. Ramsey fringes of EIT, EIA and diff-CPT signals, the experimental parameters are: Tc=5.6 ms, τ1=4.5 ms, T=1 ms, td=5.502 ms, tw=0.03 ms, Ppump=107 μW, Pprobe=57 μW, B0 = 0.87 μT.

When T = 5 ms, Ramsey fringes of clock transition with narrow linewidth of 78.2 Hz are observed, as shown in Fig. 6. The amplitude of the central fringe (central maximum minus the closest minimum) is doubled as in the CW case.

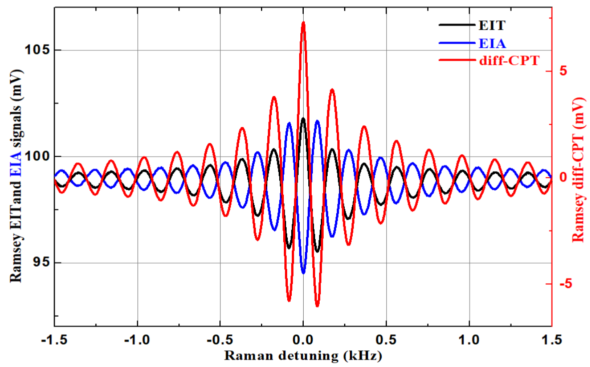

Fig. 6. Ramsey EIT, EIA & diff-CPT signals of clock transition, the experimental parameters are: Tc=7.6 ms, τ1=4.5 ms, T=3 ms, td=7.502 ms, tw=0.03 ms, Ppump=107 μW, Pprobe=57 μW.

We then measured the CPT coherence time T_2 for each channel by varying the Ramsey time T, see Fig. 7. The EIT coherence time T_2 is shorter than for EIA, and the T_2 of the differential channel is between EIT and EIA values.

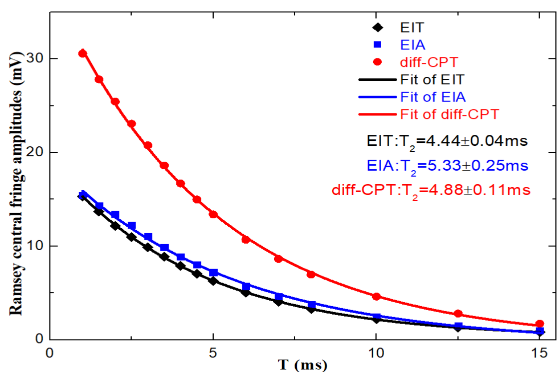

Fig. 7. CPT coherence time (T2) measurement for Ramsey EIT, EIA & diff-CPT central fringes, the experimental parameters are: Tc=τ1+T+τ2, τ1=4.5 ms, τ2=0.1 ms, td=τ1+T+0.002 ms, tw=0.03 ms, Ppump=107 μW, Pprobe=57 μW.

The linewidths of Ramsey central fringe of each channel are similar, which are plotted in Fig. 8. The linewidths are approximate to the typical value of Ramsey method for the T ⩾ 8 ms, i.e., 1/(2T), however they become narrow than the 1/(2T) as T decrease. For T ⩽ 1.5 ms, they are further narrowed by factor of two, close to 1/(4T). These narrow linewidths (1/(4T)) have also observed in a POP atomic clock with microwave detection [13] or optical polarization selective detection [14].

These results clearly show that the CDD-CPT method can be successfully applied as well with a Ramsey as with a Rabi interrogation.

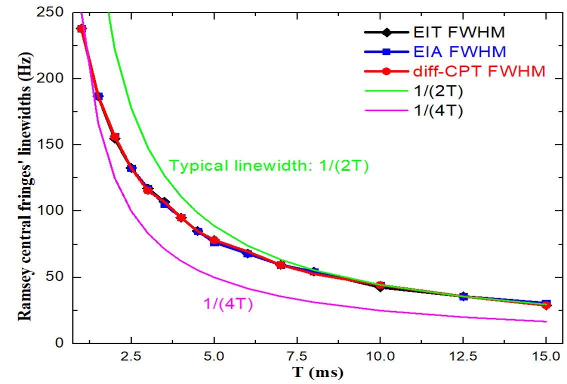

Fig. 8. Linewidths measurement for Ramsey EIT, EIA & diff-CPT central fringes, the experimental parameters are the same as Fig. 7.

V. Conclusions

We have proposed and demonstrated a scheme that allows the simultaneous detection of dark and bright resonances in a vapor cell that leads, through the use of a differential detection stage, to a resonance signal with doubled amplitude and reduced common-mode noise. Its compatibility with Ramsey method is also demonstrated. These ingredients might be the basis for the demonstration of a CPT clock with improved short- and mid-term fractional frequency stability.

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