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# Spectral narrowing of coherent population trapping resonance in laser-cooled and room-temperature atomic gas

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**Abstract.** We have investigated coherent population trapping (CPT) in laser-cooled as well as room-temperature (with and without buffer gas) rubidium atoms. The characteristic broad signal profile emerging from the two-photon Raman resonance for room-temperature atomic vapour is consistent with the theoretical calculation incorporating associated thermal averaging. The spectral width of the dark resonance obtained with cold atoms is found to be broadened, compared to room-temperature vapour cell, due to the feeble role played by thermal averaging, although the cold atomic sample significantly overcomes the limitation of the transit time broadening. An alternative way to improve transit time is to use a buffer gas, with which we demonstrate that the coherent population trapping signal width is reduced to $< 540$ Hz.

**Keywords.** Quantum interference; ultracold atoms; thermal averaging.

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## 1. Introduction

Coherent population trapping (CPT) in atomic medium is a consequence of quantum interference effect, where two excitation pathways with one common energy level are simultaneously coupled with a bichromatic light field. The optical properties of the medium is strongly modified under the CPT condition and is responsible for a variety of notable phenomena including deviation from luminal light propagation, resonantly enhanced susceptibility, lasing without inversion, possible operation as quantum gates and so on. These possibilities emerge from the optical transparency provided by the CPT states, though the medium remains optically active [1]. The associated technical uses of CPT states can be realized from the recent development in the CPT-based miniaturized atomic clock and magnetometer [2–4]. The potential use as well as investigation of various physical processes involved in the observed signal profile of the CPT states can be accomplished by using pure atomic sample, free from many of the associated complexities. Fortunately, now it is possible to generate the requisite pure atomic sample in micro-Kelvin temperature range by using laser cooling and trapping technique.

The cold atomic sample provides unique advantages as the external dynamics related to temperature and spatial distribution of atom can be controlled to the edge of quantum limit. It is also easier to manipulate the cold atomic sample in various spin states. As the associated atomic velocity is drastically reduced for the cold atomic sample, the transit time broadening giving rise to characteristic spectral width is expected to improve dramatically. It is also possible to prepare the atomic sample at various temperatures by judicially choosing the magneto-optical trap parameters [5], thereby allowing investigation pertaining to the role of thermal averaging on the width of dark resonance. Thus, realization of CPT in cold atoms will provide unique experimental platform consisting of an atomic sample with ultimate control over the external and internal dynamics to address a variety of issues at the fundamental level.

In view of technological application in atomic clock and magnetometer, the most important parameter is the spectral width of CPT resonance. Here we have investigated CPT in room-temperature atomic vapour, laser-cooled atoms, and room-temperature atomic vapour in different buffer gas environments. The motivation behind this work is to study various spectral narrowing mechanisms responsible for the observed CPT profile, namely role of thermal averaging and transit time.

The block diagram of the experimental set-up is illustrated in figure 1. The details of experimental set-ups are described in our earlier works [1,4,5]. The experimental apparatus consists of a vertical cavity surface emitting diode laser modulated at half of the rubidium-85 hyperfine ground state separation (1.517866 GHz) by a RF generator. The bichromatic field is made to interact with the atomic sample and the transmitted light is monitored with a photodetector. The diode laser is locked at the desired frequency by frequency modulation spectroscopy [6] and the transmission due to the CPT states is investigated as a function of two-photon detuning (RF modulation frequency). The atomic sample is rubidium atoms enclosed in an atomic cell without (or with) buffer gas placed in a temperature- and magnetic field-controlled environment or at ultracold temperature

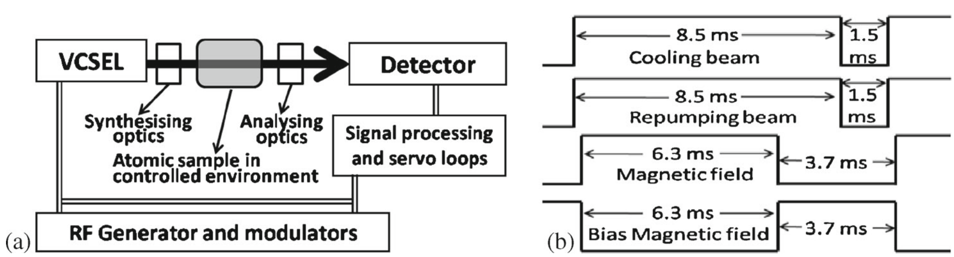


**Figure 1.** (**a**) Block experimental diagram. VCSEL represents surface emitting distributed Bragg reflector diode laser. The atomic sample is either laser-cooled atoms or atoms in vapour cell with/without buffer gas. (**b**) Sequential operation of the various magneto-optical trap parameters to realize a cold atomic sample free from the trapping beams and magnetic field. A bias magnetic field is applied in the switch-off period. The bichromatic field generated by the VCSEL laser system is switched on continuously.

generated by a magneto-optical trap. In order to generate CPT state in cold atomic sample, the magneto-optical trap parameters are sequentially operated as illustrated in figure 1b. For studying buffer gas-mediated line narrowing of the CPT signal, atomic cell filled with neon gas at 30 Torr or nitrogen gas at 25 Torr is used.

Theoretical modelling is carried out using density matrix analysis, where the imaginary part of the relevant off-diagonal density matrix element corresponds to the absorptive properties of the CPT states. Figure 2 corresponds to the theoretical result illustrating imaginary part of the susceptibility with thermal averaging as applicable for room-temperature atomic sample. The broad pedestal appearing away from the two-photon resonance is consistently observed in the experimental result illustrated in figure 2b. The

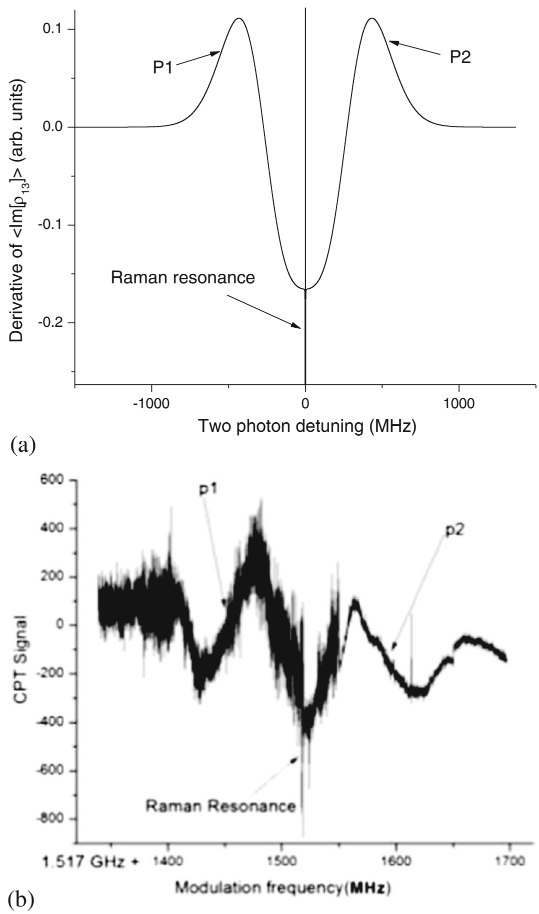


**Figure 2.** (**a**) The derivative of the imaginary part of the off-diagonal density matrix element responsible for absorptive properties of the system with thermal averaging as a function of two-photon detuning. (**b**) Corresponding experimental results exhibiting broad pedestal away from the two-photon resonance consistent with the theoretical calculations.

inclusion of thermal averaging in the density matrix calculation shows dramatic reduction in the width of the transmission profile of CPT states. On the other hand, the width of the CPT signal is found to be limited to ∼14 kHz by the transit time broadening for optimized experimental parameters. The transit time of the atomic sample can be improved by using cold atomic sample in several micro-K temperature range.

The realization of CPT in the magneto-optical trap (MOT) is a non-trivial task due to the presence of strong cooling and repumping beam along with the inhomogeneous magnetic field. The MOT beams are switched off by acousto-optic modulators and the inhomogeneous magnetic field is switched off by IGBT. Proper care is taken to avoid exponential decay of magnetic field. A small magnetic field along the propagation direction of the bichromatic field is applied to compensate the residual magnetic field during this switch-off period. The time sequences of some parameters are shown in figure 1b. The CPT signal arising solely due to cold atomic sample rather than the background atoms is verified by changing the trap parameters. The CPT signals due to cold atoms as well as atoms in vapour cell at room temperature without buffer gas are simultaneously recorded for identical experimental parameters as illustrated in figure 3. For the experimental parameters used, the CPT signal due to cold atoms is shifted ∼64 kHz from the corresponding signal obtained with atoms at room temperature. This is possibly due to the second-order Zeeman shift, as the magnetic field in the orthogonal to the laser propagation direction is not compensated. It may be noted that the width of the clock transition is not affected by the first-order Zeeman shift.

Another important observation is that the width of the CPT signal with cold atoms (∼88 kHz) is larger than the width due to CPT signal obtained with room-temperature atomic sample (∼48 kHz) for identical experimental parameters. This is despite the improvement of the transit time by a factor of ∼100 for the cold atoms compared to the room-temperature atomic sample. Therefore, the thermal averaging plays a dominant

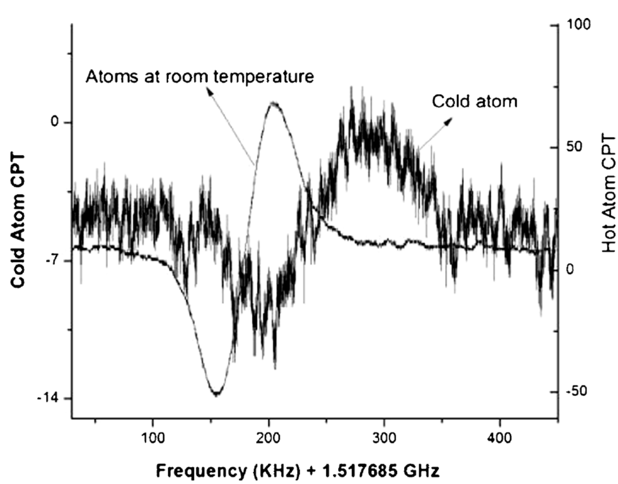


**Figure 3.** CPT signal with cold atomic sample along with atoms in room-temperature vapour cell without buffer gas. The shift of the CPT signal for the cold atom is possibly due to the second-order Zeeman shift.

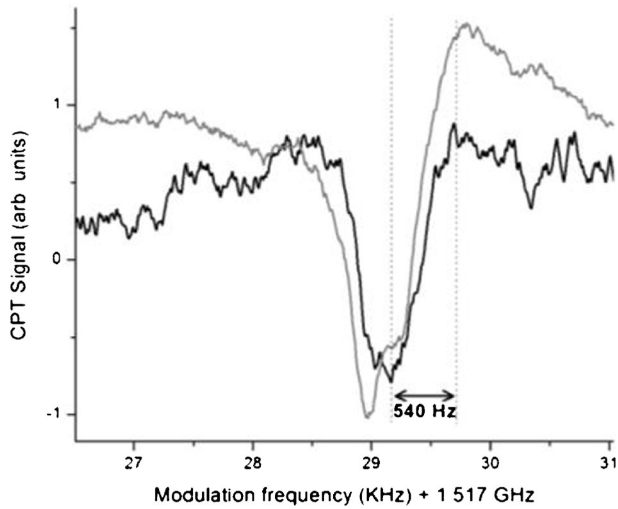


**Figure 4.** The gray (black) line shows the CPT signal obtained with Rb atoms in neon (nitrogen) buffer gas, where the RF is modulated at 450 Hz with a modulation index of 500 (200) Hz.

role in narrowing the width of the CPT signal. Consequently, the CPT signal for the cold atomic sample is broadened due to the feeble role played by the Doppler averaging at several micro-Kelvin temperature range. It may be noted that the transit time limitation of the CPT signal in vapour cell is ∼14 kHz. Therefore, width of the signal in figure 3 is limited by the 60 kHz modulation amplitude used for modulation of RF oscillator. Such high modulation index is used to improve the SNR of the CPT signal generated with the cold atomic sample.

The transit time of the atomic sample can be improved without compromising with the thermal averaging by filling the atomic cell with suitable buffer gas. The buffer gas acts as random scatters and the atoms pass through the laser beam in a zigzag path instead of crossing in a line, thereby increasing the transit time. So, we have used rubidium atomic cell filled with neon gas at 30 Torr and also with nitrogen gas at 25 Torr. The experimental results for both buffer gases are illustrated in figure 4. The width of the CPT signal for the atomic cell field with nitrogen gas is smaller due to small modulation index of the modulation frequency applied to the RF oscillator. The asymmetry observed in the CPT profile (deviation from a perfect derivative profile as illustrated in figure 3) is a characteristic of the collision with the buffer gas. As illustrated in figure 4, the width of the CPT resonance gets significantly reduced by using buffer gas filled atomic cell. Further reduction in the width of the CPT signal is in progress.

## 2. Conclusions

We have investigated and discussed various spectral narrowing mechanisms operating in transmission provided by the CPT states for cold as well as room-temperature atomic vapour. The major limitation of the transit time broadening encountered for room-temperature atomic sample is overcome by the cold atomic sample. However, the favouring role of thermal averaging is lost for the cold atomic sample and collectively the CPT signal has a larger width compared to room-temperature atomic vapour. Buffer gas filled atomic cell significantly improves the transit time resulting in ultranarrow width of $\sim$540 Hz. The width of the CPT signal can be further decreased by optimizing the experimental parameters.

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