Optics Communications 356 (2015) 378–388

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Investigation of high-contrast velocity selective optical pumping resonance at the cycling transition of Cs using fluorescence technique

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ARTICLE INFO

Article history:
Received 2 April 2015
Received in revised form
3 August 2015
Accepted 7 August 2015

Keywords:
Thin Cell
Optical Pumping
Laser frequency stabilization
Sub-Doppler spectroscopy
Wall collision
Cold atom experiments

ABSTRACT

A high contrast (~48%) Velocity Selective Optical Pumping (VSOP) resonance at the closed transition $F_g=4\rightarrow F_e=5$ of Cs-D_2 line is obtained in the fluorescence signal under co-propagating pump-probe configuration. We use a 5.2 μm cell operating at reduced temperature (~55 °C) and the intensity of the pump-laser is kept lower than that of the probe-laser. The observed sharp narrow structure is suitable for side-arms frequency-locking of the cooling- (i.e. probe-) laser in a cold atom experiment, with possibility for "$-\Gamma$" to "-4Γ" red-detuning and "$+\Gamma$" to "$+10\Gamma$" blue-detuning using the standard properties of the commercially available electronics. We have developed a theoretical model corresponding to the thin cell, incorporating the atomic time-of-flight dependent optical pumping decay rate to describe the dimensional anisotropy of the thin cell. The model shows good qualitative agreement with the observation and simulates as well the cases of cells with smaller thickness. It also describes correctly the temperature dependence of the line broadening and shows the potential for further optimization and red-shift detuning above "-4Γ". It may be of interest for further development of miniaturized modules, like the recently developed portable small magneto-optical traps.

1. Introduction

Atomic coherence induced by atom-laser interaction may lead to interesting coherent resonances of sub-natural linewidth that are drawing huge interest since the first observation of the Coherent Population Trapping (CPT) [1], thanks to the multiple applications in both basic and applied sciences-laser cooling [2], induced transparency [3], lasers without inversion [4], high-precision magnetic field measurement [5] and many in different direction. It is significantly higher for the atoms others [6]. Apart from the coherent resonances, different kinds of saturation and optical pumping resonances are observed [7], depending upon the specific atom-laser coupling schemes. Investigation of such coherent and incoherent resonances has been reported so far in a great depth for the conventional cm size vapor cell. However, miniaturization of the cell's dimensions becomes important for nowadays miniature devices and quantum sensors ([8] and the references there-in). A specific approach of cell miniaturization is represented by the cells with reduced, down to the micrometer or sub-micrometer range, length (thickness). This kind of cells introduces a very high degree of anisotropy in the dimensions and modifies the shape of the observed spectra. In 1992, it was first predicted theoretically [9] how such a dimensional anisotropy can strongly influence the observed spectra. In such cell, the rate of the atom-wall collisions significantly differs for the atoms propagating propagating orthogonally to the windows rather than those moving in parallel. When such a cell is irradiated with a laser beam propagating perpendicular to the cell windows, the projection of the atomic velocity to the laser-beam direction is zero for the atoms moving in parallel to the windows. These atoms which are called zero velocity group of atoms interact with the laser for their flight through the beam and do not suffer any atom-wall collisions-similarly like in the classical cm-size cells. However, for the non-zero velocity groups of atoms, the rate of atom-wall collision increases and it becomes maximal for those atoms moving along the laser beam i.e. perpendicular to the cell windows. As the atom-wall collisions are inelastic, they result in an isotropic redistribution of the ground-state population [6] which is opposite to the optical pumping effect. Therefore, the efficiency the optical pumping process become velocity-group dependent and is called Velocity Selective Optical Pumping (VSOP). It is much more efficient in the center of the resonant line (for the "zero velocity group" of atoms) rather than in the wings (for the "non-zero velocity groups").

A series of experiments have been demonstrated in thin cells with thickness varying between 10 μm and 100 μm [10,11],

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http://dx.doi.org/10.1016/j.optcom.2015.08.013
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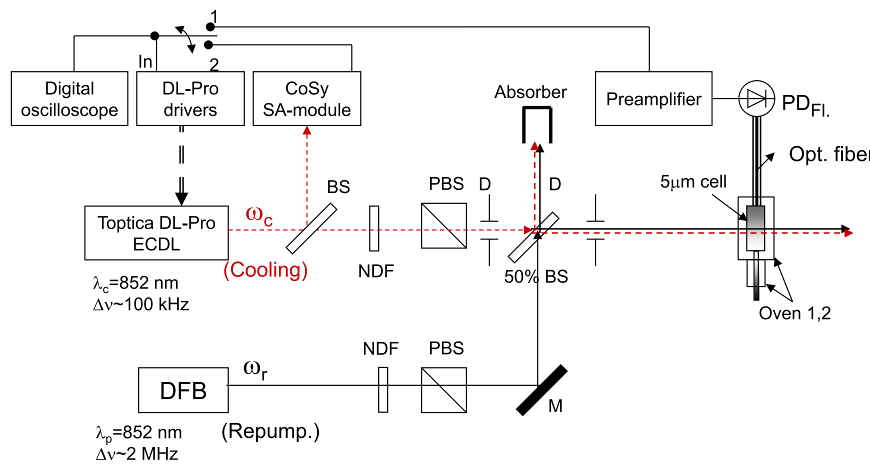

Fig. 1. Experimental setup. ECDL – External Cavity Diode Laser (cooling) and DFB – Distributed Feedback Laser (repumping) tuned at λ=852 nm and having emission linewidth of 100 kHz and of 2 MHz respectively. NDF – Neutral Density Filter, PBS=Polarization Beam Splitter, D – iris diaphragm, M – 100% mirror. BS-amplitude Beam Splitter, "CoSy"-the standard module for Saturated Absorption Spectroscopy of the DL-pro system.

showing the influence of the VSOP-effect on the Saturated Absorption Spectroscopy (SAS). As a spectacular result, the Cross-Over (CO) resonances originating from the velocity groups of atoms propagating along the laser beam, get significantly attenuated and a modified SAS-spectrum was demonstrated with vanishing CO resonances. These experiments demonstrate also how the VSOP processes are responsible for the formation of dips in the spectrum centered at the positions of the open transitions even for a single-beam illumination. Resonant spectral structure is also formed at the closed transition, but due to the absence of optical pumping its amplitude is significantly smaller and results from the saturation of the absorption process, increasing with the laser intensities. In particular, the authors of [10,11] have predicted for further application of the thin cells as a suitable tool for laser frequency stabilization. Further development of the cells with strong dimensional anisotropy [12–14] make possible to decrease the cell thickness down to the nanometer range (nano-cell or Extremely Thin Cell (ETC)). A general overview of the novel effects observed in these cells of different nanometric thickness is presented in [15]. In [16] a detailed study of the CO-resonance-suppression process is presented. This specific study is of importance for frequency stabilization and allows determining the lower limit of cell-thickness to get suppressed the signature of the CO-resonance on the spectrum.

As the laser frequency stabilization is an application of basic interest in atomic physics, particular attention deserves a group of studies, demonstrating this technique on spectra from thin or extremely thin cells [17,18]. In [17] effective frequency stabilization is demonstrated by using Rb vapor cell with thickness of 390 nm ($\lambda/2$ of the Rb D_2 line). The authors of [17] show that reliable signals for frequency stabilization with very good signal-to-noise ratio can be obtained using such a thin column of atomic vapor. The necessary cell temperature is about 120 C (Figs. 2 and 5 of [17]). In such a high degree of dimensional anisotropy just single-beam spectra shows completely resolved hyperfine transitions. The authors of [18] demonstrate effective laser frequency stabilization as well, by using essentially broader Cs cell (thickness of ~150 μm). The thicker atomic vapor column allows reducing the cell temperature down to 80 °C. However, the used single beam spectroscopy shows significant compromise of the resonant structures contrast at this thickness, essentially below that of the classical SAS (Fig. 2a of [18]). To obtain reliably big resonance structures the authors of [18] use the 1st and 3rd derivative technique to demonstrate effective laser frequency stabilization

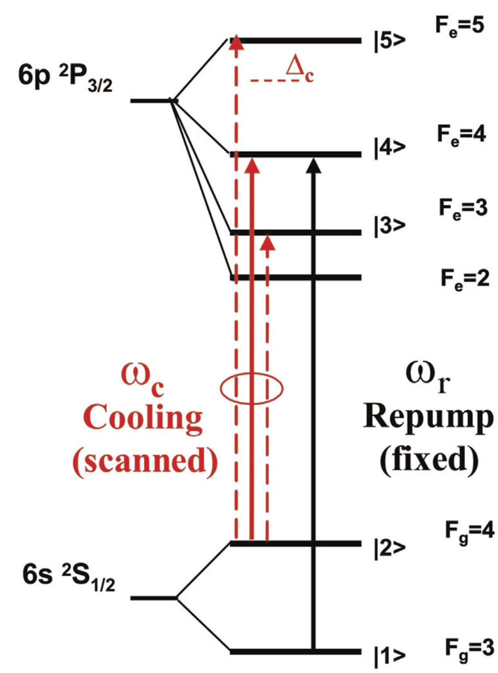

Fig. 2. Energy-level diagram for ^{133}Cs D_2 line, where the cooling laser transitions (red arrows) are distinguished from the repumping laser addressed transition (black arrow). The solid arrows indicate the Λ-system formed when the Raman condition is satisfied and EIT-resonance is observed. Δ_c indicates the red-detuned position of the cooling laser. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with variations below 0.8 MHz and Allan variance of the error signal below 5×10^{-11} for 200 s. Based on cells with largely different degree of dimensional anisotropy, by means of two different techniques, these two research examples how the impact of the cell thickness on a single-beam absorption spectrum can be used for frequency stabilization purposes. However, because of the contrast of the obtained spectral features, both of the papers demonstrate the use of the open transitions from the lower ground-state of the corresponding alkali atom, but do not use the closed (cycling) transition. As the demonstrated in [18] VSOP-resonances on the open transitions are with so small amplitude, the corresponding structure for the closed transition will be even much smaller because it results only from the two-level saturation processes. Moreover, the necessary for that higher optical power