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Laser frequency offset locking by marrying modulation sideband with the two-color polarization spectroscopy in a ladder-type atomic system

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ABSTRACT

We present an investigation of two-color polarization spectroscopy (TCPS) based on cesium $6S_{1/2}$–$6P_{3/2}$–$7S_{1/2}$ (852 nm + 1470 nm) ladder-type system in a room-temperature vapor cell. The 1470 nm laser can be offset locked by TCPS combining with frequency modulation sideband. This locking scheme offers a method of modulation-free and conveniently tunable the lock point of laser frequency relative to an excited state transition, and may have many applications such as in two-color magneto-optical trap, diamond-level structure four-wave mixing experiments.

1. Introduction

Polarization spectroscopy (PS) is first demonstrated by Wieman and Hänsch [1], where a circularly-polarized pump laser induces the optical anisotropy of atomic medium, and is then detected by a counter-propagating linearly polarized probe laser. The obtained dispersive signal is widely used in laser frequency locking without frequency modulation [2,3]. In this traditional PS, the frequency of pump laser is the same with probe laser, and they are usually from a single laser, and tuned to the same transition line between a ground state to an excited state. Recently the PS in a ladder-type atomic system is reported, and called as two-color polarization spectroscopy (TCPS) [4–6]. Here the pump and probe lasers, with different wavelength, are tuned to the lower and upper transitions, respectively. The TCPS for the $6S_{1/2}$–$6P_{3/2}$–$7S_{1/2}$ transitions of cesium atoms is reported by Carr *et al.* [4] in experiment and Noh [5] in theory, and the TCPS on the $5S_{1/2}$–$5P_{3/2}$–$5D_{5/2}$ transitions of ^{87}Rb atoms is experimentally demonstrated by Kulatunga *et al.* [6]. The TCPS is a kind of Doppler-free spectroscopy technique in the transition between excited states, and provides a dispersive signal for laser frequency stabilization to an excited-to-excited state transition without frequency modulation. Compared with the TCPS, the optical–optical double resonance (OODR) [7,8] and double-resonance optical pumping (DROP) [9,10] are also very important techniques for obtaining Doppler-free spectrum in the transition between atomic excited states, but the laser frequency locking using an OODR or DROP spectrum often needs direct or indirect frequency modulation to lasers [8,9,11]. For the TCPS, it can serve as a frequency discriminating signal for frequency stabilization of upper laser, the whole experimental system completely has no frequency modulation when the lower laser is also locked using PS, so the further improvement of the frequency stability of the locked upper laser is expected, which is very significative in optical fiber communication [12].

Moreover, the frequency of upper laser is often required to be offset locked to the atomic resonance line in some experiments such as two-color magneto-optical trap [13,14], diamond-level structure four-wave mixing [15,16]. Acousto-optic modulator (AOM) has been conventionally used in experiment, but limited by its bandwidth and central frequency, the laser frequency is continuously tuned in a range of several tens MHz [14]. An alternative method is that the frequency detuning of the upper laser (Δ_{upper}) to resonant line is controlled by adjusting the detuning of the lower laser (Δ_{lower}) under the two-photon resonance condition $\Delta_{\mathrm{upper}} + \Delta_{\mathrm{lower}} = 0$ (for example electromagnetically induced transparency and absorption, OODR spectrum, and

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DROP spectrum), and its tuning range of laser frequency is up to ~1–2 GHz off atomic resonance line [17–19] limited by the interaction of atoms and laser fields in the Doppler width. In our experiment, combining with the frequency modulation sideband by a fiber-pigtailed waveguide-type electro-optical phase modulator (EOM, EOSPACE), we offset locked a laser to the upper or lower modulation sideband using the TCPS, and the lock point of the upper laser relative to the resonance line can be conveniently adjusted by changing radio frequency on EOM from a few tens MHz (Limited by the line-width of the TCPS spectrum) to tens GHz even bigger, which mainly depends on the bandwidth of EOM. This technique offers a modulation-free method (need no lock-in amplifier in the whole experimental system) suitable for laser frequency stabilization to the upper transition with the conveniently tunable detuning to the resonance point in a ladder-type atomic system.

2. Principle and experimental setup

For the TCPS of an excited state transition, the birefringence in a medium (here, cesium atoms) is induced by the circularly-polarized pump laser working on the lower transition (852 nm), and interrogated with a counter-propagating weak linearly-polarized probe laser operating on the upper transition (1470 nm), the relevant hyperfine levels of cesium atoms are shown in Fig. 1. The spontaneous emission decay rates of the excited state $6P_{3/2}$ and $7S_{1/2}$ are $\Gamma_{6P}=2\pi\times5.2$ MHz and $\Gamma_{7S}=2\pi\times3.3$ MHz, respectively.

A schematic of experimental setup is shown in Fig. 2. A commercial grating-feedback external-cavity diode laser (ECDL) at 852 nm (DL1: Toptica DL-100) serves as the pump laser, and is stabilized to the $6S_{1/2}$ $(F=4)\rightarrow6P_{3/2}$ $(F'=5)$ transition with the modulation-free PS. The the probe laser is provided with ECDL at 1470 nm with linewidth <300 kHz (DL2: Newport, TLB-6326), and is scanned over the $6P_{3/2}$ $(F'=5)\rightarrow7S_{1/2}$ $(F''=4)$ transition. The mode of the probe laser is monitored with a confocal F–P cavity with a finesse of ~100 and a free spectrum range (FSR) of ~2.5 GHz. The scan frequency interval of probe laser is calibrated using a fiber-pigtailed waveguide-type EOM with a large bandwidth (~10 GHz), which is drived by an analog signal generator (Agilent, E8257D). A circularly-polarized 852 nm pump beam with a $1/e^2$ diameter ~2.0 mm generated by a quarter-wave plate and a linearly-polarized 1470 nm probe beam with a $1/e^2$ diameter ~1.2 mm are counter-propagating, and overlapped in a cesium vapor cell (25 mm in diameter, 75 mm in length) via dichroic filters. The cesium vapor cell is wrapped with three-layer μ-metal sheet in order to decrease the influence of background magnetic field. To obtain the TCPS between the $6P_{3/2}$ $(F'=5)\rightarrow7S_{1/2}$ $(F''=4)$ transition, a polarization beam splitter (PBS) cube oriented at an angle of 45° related to the polarization direction of the 1470 nm probe beam splits the probe electric field into orthogonal linear components, which are detected using a balanced receiver (PD1, NewFocus, model 2117). The 852 nm pump laser passing through the vapor cell is separated by another dichroic filter, and then is detected by a receiver (PD2, NewFocus, model 2107) for registering DROP spectrum also corresponding to the same transition between the $6P_{3/2}$ $(F'=5)\rightarrow7S_{1/2}$ $(F''=4)$ excited states [9,10]. The obtained TCPS as frequency discriminating signal is fed back to the piezoelectric transducer (PZT) of 1470 nm laser's cavity for frequency stabilization.

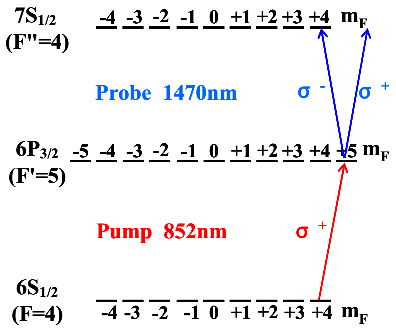

Fig. 1. Relevant hyperfine levels and Zeeman sublevels for the two-color polarization spectroscopy in the cesium $6S_{1/2}$–$6P_{3/2}$–$7S_{1/2}$ ladder-type system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

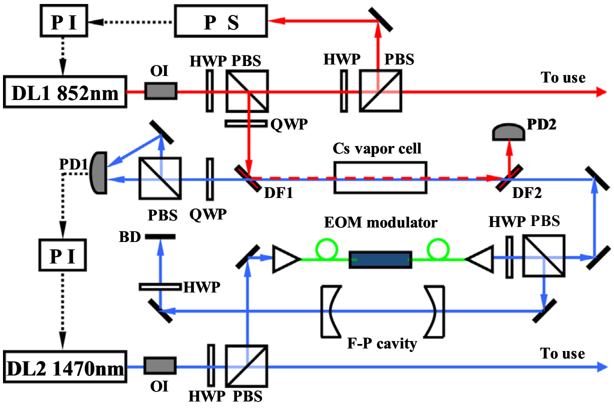

Fig. 2. Schematic diagram of setup for the two-color polarization spectroscopy and laser frequency stabilization of the probe laser. Keys to the figure: DL1(DL2): external-cavity diode lasers; PS: polarization spectroscopy; EOM: phase-type electro-optical modulator; OI: optical isolator; P–I: proportion and integration amplifier; F–P cavity: Fabry–Perot cavity; DF: dichroic filter; PBS: polarization beam splitter cube; HWP: half-wave plate; QWP: quarter-wave plate; PD: photodiode; BD: beam dump. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

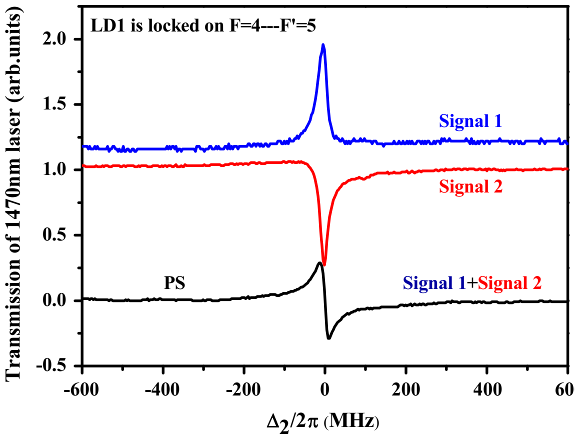

Fig. 3. Experimental spectra. Individual signal 1(blue trace) and signal 2 (red trace) from one of photodiodes of balanced receiver (PD1), which are usually called as optical–optical double resonance (OODR) spectra; signal 1+ signal 2 (black trace) is a dispersive profile for two-color polarization spectroscopy (TCPS) of the $6P_{3/2}$ $(F'=5)\rightarrow7S_{1/2}$ $(F''=4)$ transition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Experimental results and discussions

When the 852 nm pump laser is locked to the $6S_{1/2}$ $(F=4)\rightarrow$ $6P_{3/2}$ $(F'=5)$ transition using the modulation-free PS technique, and the 1470 nm probe laser is scanned over the $6P_{3/2}$ $(F'=5)\rightarrow$ $7S_{1/2}$ $(F''=4)$ transition, a typical TCPS (signal 1+signal 2) is shown