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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.

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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 significant 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 $\Delta_{\text{upper}} + \Delta_{\text{lower}} = 0$ (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 $\Gamma_{6P} = 2\pi \times 5.2$ MHz and $\Gamma_{7S} = 2\pi \times 3.3$ 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 $6S_{1/2} (F=4) \rightarrow 6P_{3/2} (F=5)$ 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 $6P_{3/2} (F=5) \rightarrow 7S_{1/2} (F=4)$ 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 driven 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 $6P_{3/2} (F=5) \rightarrow 7S_{1/2} (F=4)$ transition, a polarization beam splitter (PBS) cube oriented at an

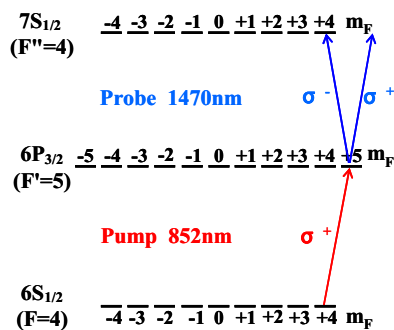


Fig. 1. Relevant hyperfine levels and Zeeman sublevels for the two-color polarization spectroscopy in the cesium $6S_{1/2}$ - $6P_{3/2}$ - $7S_{1/2}$ ladder-type system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

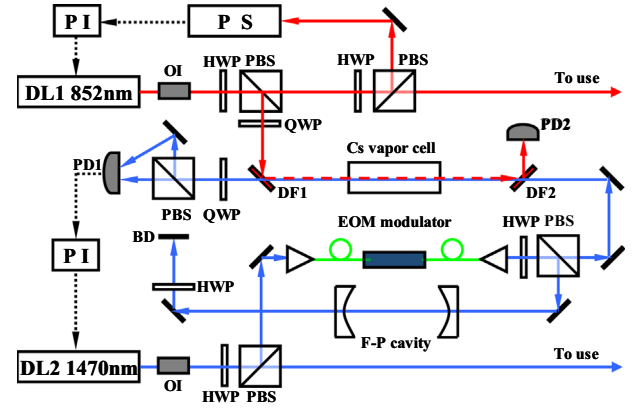


Fig. 2. Schematic diagram of setup for the two-color polarization spectroscopy and laser frequency stabilization of the probe laser. Keys to the figure: DL1(DL2): external-cavity diode lasers; PS: polarization spectroscopy; EOM: phase-type electro-optical modulator; OI: optical isolator; P-I: proportion 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.)

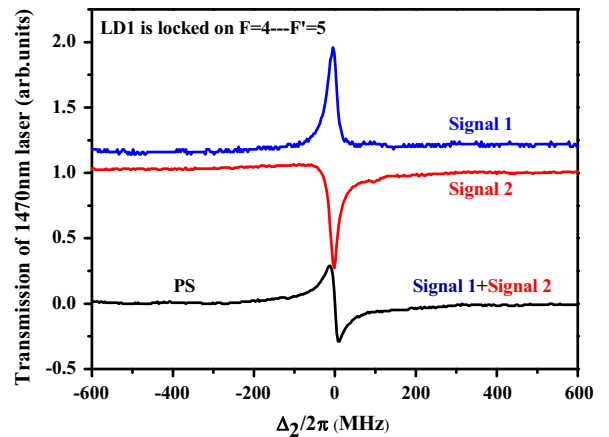


Fig. 3. Experimental spectra. Individual signal 1 (blue trace) and signal 2 (red trace) from one of photodiodes of balanced receiver (PD1), which are usually called as optical-optical double resonance (OODR) spectra; signal 1 + signal 2 (black trace) is a dispersive profile for two-color polarization spectroscopy (TCPS) of the $6P_{3/2} (F=5) \rightarrow 7S_{1/2} (F=4)$ transition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 $6P_{3/2} (F=5) \rightarrow 7S_{1/2} (F=4)$ 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.

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

in Fig. 3. Signal 1 and signal 2 are from one of photodiodes of balanced receiver (PD1), and are usually called as the OODR spectra, one of the most sophisticated techniques for obtaining a Doppler-free spectrum in the transition between atomic excited states [7,8]. For the data presented in Fig. 3, the power of the probe and pump laser beams are 0.64 mW and 0.12 mW, respectively. The power of the pump is smaller than the probe, we expect to obtain a narrower line-width spectrum taking advantage of coherent effect of atomic system, because the coherent effect will be destroyed with the increasing pump intensity [10,11,17]. So when the power of the pump is increased, the line-width of observed TCPS is obviously broadened, and eventually evolved into Autler-Townes splitting (ATS) for the stronger pump, as shown in Fig. 4(a). The frequency axis of 1470 nm probe laser is calibrated using a fiber-pigtailed phase-type waveguide EOM driven by an analog signal generator with 100 MHz sinusoidal wave and a typical radio-frequency output of ~ 14 dBm. We also simultaneously recorded the DROP spectra by PD2 under the same experimental condition with the TCPS in Fig. 4(a). The ATS is intuitively displayed in the evolution of DROP spectra with the increase of the 852 nm pump power (~ 0.061 – ~ 1.040 mW) as shown in Fig. 4(b), this will help us to easily understand the unusual ATS lineshapes in the TCPS in Fig. 4(a).

TCPS, DROP and OODR are three kinds of spectroscopic techniques for getting the spectra for transitions between atomic excited states, and all can be used to stabilize the frequency of the upper laser (DL2). For laser frequency stabilization using OODR and DROP spectra, there is a need for frequency modulation for the DL1 (indirect modulation) or DL2 (direct modulation), and then we can obtain a dispersion-like frequency-discriminating signal of the OODR or DROP spectrum by the phase sensitive detection

via the lock-in amplifier according to the reference signal for the frequency modulation of the DL1 or DL2 laser. Finally, the obtained error signal is electrically fed back to the DL2 laser. In this paper, when we adopt the TCPS to lock the DL2, and DL1 is also locked using PS between the ground state to the excited state, there is no frequency modulation in the whole experimental system for the further improvement of frequency stability, and it provides a sort of laser frequency stabilization to the excited state transitions without the need of expensive lock-in amplifier.

Fig. 5(a) shows the TCPS accompanied with 200 MHz radio sideband signal for frequency stabilization of DL2 laser, and the TCPS spectrum for $F=5-F''=4$ asymmetric with respect to the zero position is maybe due to the nonlinear scanning of the upper laser and the non balanced detection on PD1. In order to avoid the happening of ATS in TCPS, the power of the 852 nm pump laser is set to 100 μ W according to Fig. 4, and the power of the 1470 nm probe laser is 300 μ W. To increase the magnitude of the TCPS from the ± 1 -order sidebands, the modulation signal power on EOM is set to ± 19 dBm, and here the slope of the dispersion-like signal for the -1-order sideband is 76.8 MHz/V. Then, this error signal (the -1-order sideband) is fed back to the PZT of DL2 laser by a PID (proportional, integral and differential amplifier) module for frequency locking. So the lock point of DL2 laser frequency is $+200$ MHz offset from the $6P_{3/2}$ ($F=5$) \rightarrow $7S_{1/2}$ ($F''=4$) resonant transition. Fig. 5(b) shows the frequency fluctuation of DL2 laser with ± 1.2 MHz and ± 8.5 MHz for locking on and the free running case, respectively. The frequency stability of the DL2 laser after locking is probably limited by that of an analog signal generator (Agilent, E8247D) driving EOM, which can be further stabilized by an atomic clock in future. At the same time, a higher

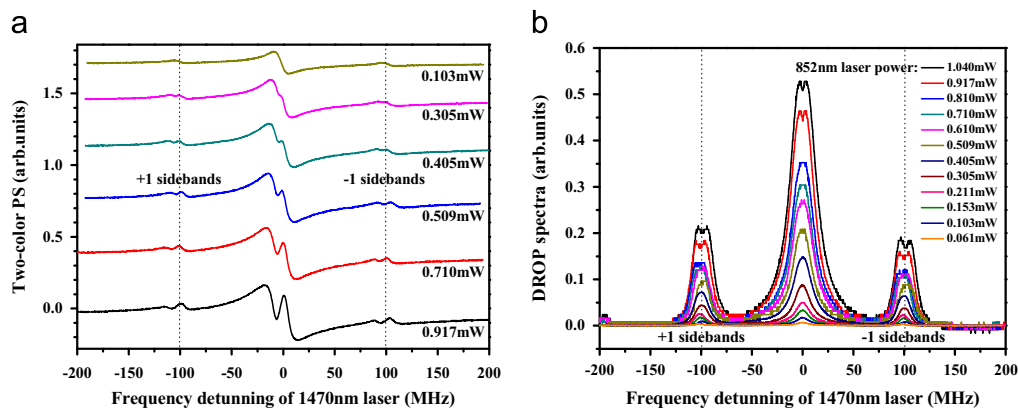


Fig. 4. Evolutions of the TCPS (a) and the DROP spectra (b) with the increase of 852 nm pump power (0.103–0.917 mW). The frequency axis is calibrated using a fiber-pigtailed phase-type waveguide EOM driven by 100 MHz sinusoidal wave.

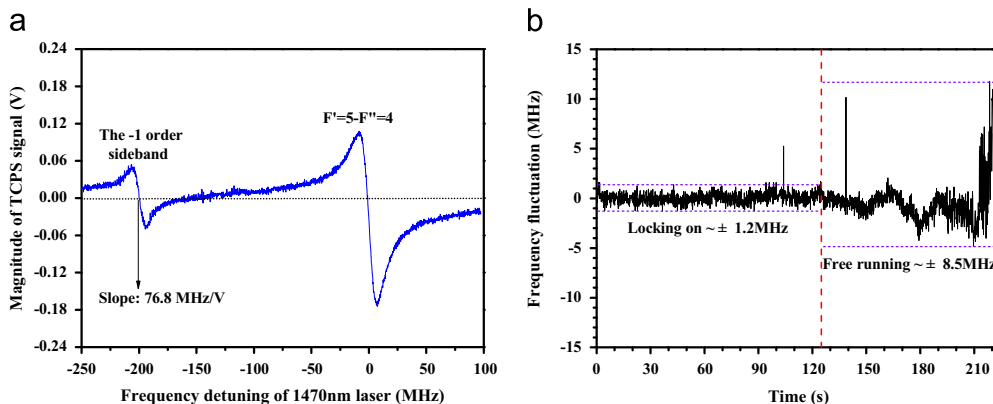


Fig. 5. (a) The TCPS with 200 MHz radio frequency sideband of the $6P_{3/2}$ ($F=5$) \rightarrow $7S_{1/2}$ ($F''=4$) transition for frequency stabilization of DL2 laser. (b) Frequency fluctuation of DL2 laser for locking on and the free running case.

stability of DL2 might be obtained by feeding back the high-frequency component of the feedback signal to the 1470 nm laser current. At present, the precision of locking frequency is enough for many relevant experiments such as two-color laser cooling [13,14], four-wave mixing in a ladder-type atomic system and so on [15,16]. A distinctive advantage in our scheme is that the DL2 laser can be offset locked to an excited state transition with a large convenient tuning range of frequency detuning, which only depends on the response of EOM to radio frequency signal with greater than 3 GHz in our experiment.

4. Conclusion

In conclusion, we investigate the TCPS in a room-temperature cesium vapor cell based on the $6S_{1/2}$ – $6P_{3/2}$ – $7S_{1/2}$ ladder-type atomic system. The unusual lineshapes of ATS in TCPS can be easily understood by the aid of the obtained DROP spectra under the same experimental condition. We have developed a modulation-free scheme to offset lock the frequency of a laser to a transition between excited states with a large and convenient tuning range of frequency detuning to the resonant point, combining the technique of radio frequency modulation to EOM. This method of offset locking frequency will be applied into our two-color (852 nm+1470 nm) magneto-optical trap.

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