A novel scheme of Doppler-free spectroscopy by differential detection

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***Abstract*—We propose and implement a differential detection scheme of Doppler-free spectroscopy. By setting the proper relative polarization direction between the linearly polarized probe and pump beam, which are spatially counter-propagated and overlapped, simultaneous enhanced absorption and transmission are observed by detecting the parallel and perpendicular polarization components of the transmitted probe beam. The differential signal with improved signal-to-noise ratio (SNR) is also obtained, which is desired for compact optical reference, high-resolution spectroscopy and so on.**

Keywords—Doppler-free, Enhanced absorption and transmission, differential detection, compact optical reference

I. Introduction

Doppler-broaden is caused by the inhomogeneous distribution of atomic velocities and can be eliminated or suppressed by Doppler-free techniques such as saturation absorption spectroscopy (SAS) [1-2], polarization spectroscopy [3-4], modulation transfer spectroscopy [5], etc. Saturation absorption spectroscopy is widely used because of its simplicity, which measures the absorption of the probe beam saturated by a counterpropagating pump beam and then uses the probe beam minus the reference beam to obtain a Doppler-free signal with enhanced transmission or absorption.

The transition from enhanced transmission to enhanced absorption has been observed in many studies in the absorption spectrum, and the mechanism is briefly discussed [1-2]. Most saturated absorption spectroscopy only uses enhanced transmission or absorption signals, but we use enhanced transmission and absorption signals at the same time to get a higher signal-to-noise ratio differential signal in this paper.

In this paper, we propose a new scheme. With the special pump-probe polarization configuration, simultaneous enhanced transmission and absorption are observed by detecting the parallel and perpendicular polarization components of the probe beam. Compared with the traditional saturation absorption spectroscopy with enhanced transmission shape signal, Doppler-free signals with simultaneous enhanced transmission and absorption are obtained in our novel scheme, more importantly, differential signals between them are also observed with higher signal-to-noise ratio (SNR) [6-8].

II. Experiment Setup

The experimental setup is similar to the one in [7], the main difference is a monochromatic light rather than a bichromatic light is used in this new scheme. The light source is a distributed Bragg reflector (DBR) laser tuned to the ^{87}Rb D$_1$ line at 795 nm. The cell temperature is stabilized at approximately 30 °C. The pure ^{87}Rb-isotope-enriched cylindrical vapor cell (diameter 20 mm, length 50 mm) is surrounded by two layers of permalloy magnetic shield. No static magnetic field is applied.

After passing through a beam splitter (BS), the linearly polarized light beam (pump beam) interacts with the ^{87}Rb atoms. The diameter of the Gaussian-shape beam incident in the cell is about 1.5 mm. Thanks to a quarter-wave plate and mirror, the probe beam is obtained which is spatially counter-propagated and overlapped with the pump beam. In order to study the effect of the probe beam's polarization, the angle between the polarization axis of the probe beam and the pump beam is labeled θ. The transmitted light of the probe beam is spatially separated by the beam splitter, whose orthogonal components are separated by half-wave plate and polarization beam splitter (PBS), and sent to balanced detectors.

III. Experiment Result

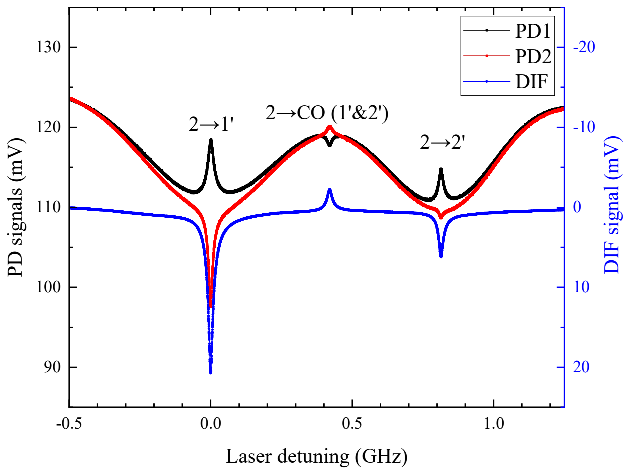

Fig. 1. Experimentally obtained typical enhanced transmission (black), enhanced absorption (red) and differential (blue) spectrum in the D$_1$ line of ^{87}Rb. 2, 1′ and 2′ stand for $|F=2\rangle$, $|F'=1\rangle$, and $|F'=2\rangle$, respectively. The experimental parameters are as follows: $T_{cell}=30\,℃$, $P_L=50\,\mu W$, $\theta=-30\,°$.

Figure 1 demonstrated the observed enhanced transmission (black), enhanced absorption (red) with laser power $P_L = 50\ \mu W$ and the relative polarization angle $\theta = -30°$, i.e., the Doppler-free spectroscopy with simultaneous absorption reduced and enhanced signals with ground state $|F = 2\rangle$ in the D_1 line of ^{87}Rb. Their differential signals (blue) are also plotted. Compared with enhanced transmission or absorption signals, the differential signals in our novel scheme are featured with increased amplitude and narrow linewidth, and its Doppler-broaden background is almost eliminated, which is desired for high-performance and robust laser frequency locking.

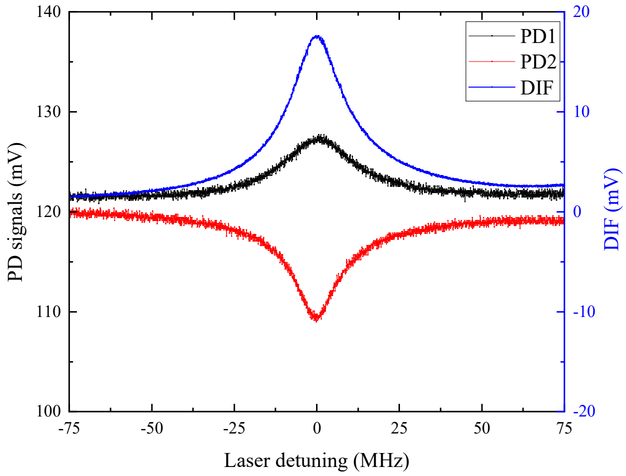

Fig. 2. The zoom-in enhanced transmission, enhanced absorption and differential (reversed) signals of the transition $|F = 2\rangle \rightarrow |F' = 1\rangle$ in figure 1.

A closer view as shown in Fig. 2, the enhanced transmission, enhanced absorption, and differential signals are obtained with the same conditions as Fig. 1. The amplitude of the differential signals is about 20 mV, almost twice that of enhanced transmission and absorption signals. The SNR improvement of the differential signal is also clearly demonstrated.

For further investigation, the noise spectral densities of enhanced transmission, enhanced absorption, and differential signals were measured using a spectrum analyzer at half maximum. The results are shown in Fig. 3. At the Fourier frequency of 100 kHz, the noise levels of enhanced transmission and absorption signals are almost the same, at about 2×10^{-7} V/√Hz, while the noise of differential signal is about 4×10^{-8} V/√Hz. After the difference, the noise of the signal is reduced by about 5 times, which indicates that the scheme can suppress the common mode noise from the laser, increase the SNR of the signal, and improve the short-term stability of the laser frequency.

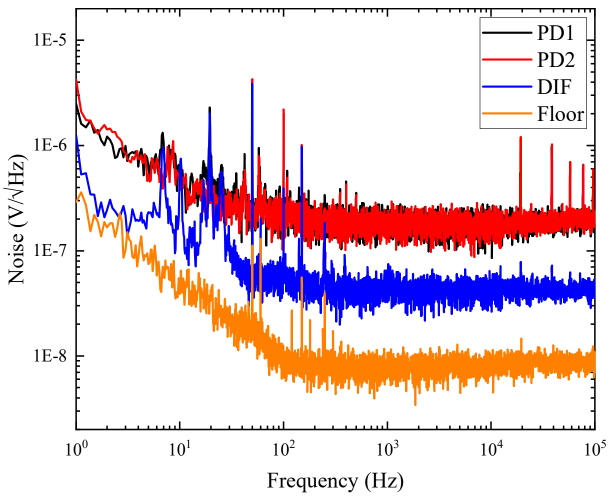

Fig. 3. Noise spectra of enhanced transmission (black), enhanced absorption (red) and differential (blue) signals.

IV. Conclusions

We propose and demonstrate a novel differential Doppler-free spectroscopy by detecting the coexistence of enhanced transmission and absorption, which can obtain Doppler-free atomic resonant signals with increased SNR. This method can potentially improve the frequency stability of laser frequency locking, thus leading to a compact and high-performance optical reference.

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