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Ultra-narrow linewidth optical filter based on Faraday effect at isotope ^{87}Rb 420 nm transitions

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ABSTRACT

An ultra-narrow linewidth optical filter with isotope ^{87}Rb vapor at 420 nm, within the best waveband 400–500 nm for deep sea communication is achieved for the first time. The Faraday effect, circular dichroism, and nonlinear saturation techniques are utilized to narrow the bandwidth from previous 2.5 GHz to about 15 MHz level on the energy transition $5S_{1/2} \rightarrow 6P_{3/2}$. By changing the temperature and magnetic field, the maximum transmission is obtained when the temperature and the magnetic field of the ^{87}Rb cell are at 100 °C and 12 G. We discuss the varying influences of temperature, magnetic field, and pump power on the transmission of the atomic filter. The maximum single peak transmission at $5S_{1/2}$, $F = 2 \rightarrow 6P_{3/2}$, $F' = 3$ transition is 2.1% with a bandwidth of 17.8 MHz, and 1.9% at the $5S_{1/2}$, $F = 2 \rightarrow 6P_{3/2}$, $F' = 2,\ 3$ (cross-over) transition with that of 14.2 MHz. The calculated equivalent noise bandwidth of this system is 32.5 MHz. Compared with the conventional Faraday anomalous dispersion optical filter, the bandwidth of our system is narrowed at least two orders of magnitude and is closer to the natural linewidth. This ultra-narrow linewidth filter has the potential to be applied to submarine communication or the pump laser in a four-level Rb-based active optical clock.

1. Introduction

Optical filters based on atomic energy transitions are attractive for fundamental researches and practical applications where the bandwidth is a critical parameter [1,2]. Ultra-narrow linewidth optical filters with high sensitivity, high spectral selectivity, and frequency stability show promise for various optical system-based applications, such as optical communications in free space [3], laser radar remote sensing [4], the generation of narrowband quantum light [5–7], and the pump laser in four-level Rb-based active optical clocks [8,9]. Compared with the conventional interference filters, Faraday anomalous dispersion optical filters (FADOFs) have the merits of narrow bandwidth, background rejection, mechanical robustness, imaging capability, and high transmission. Therefore, FADOFs have been developed for several elements, such as Cs [10,11], Rb [12,13], K [14,15], Na [16], and Ca [17].

Two important indexes are used for evaluating the performance of semiconductor lasers: linewidth and frequency stabilization. In order to narrow the linewidth, semiconductor lasers are locked on atomic or molecular spectral lines using electric or optical feedback to achieve stable output frequency. It is necessary to provide a reference for frequency stabilization with narrow spectral linewidth. Currently, the free running linewidth of commercial semiconductor lasers is 15–100 MHz, which meets the practical requirements in some common scientific applications. However, for laser cooling, atomic trapping, quantum frequency standards, and other basic researches, much narrower-linewidth laser sources are required. Compared with general spectroscopy, laser spectroscopy technology can improve the resolution of the spectrum as a result of eliminating Doppler broadening.

The means to eliminate Doppler broadening is through a saturated absorption spectroscopy, polarization spectroscopy or two-photon spectroscopy [18–20]. In recent years, theoretical and experimental studies on ultra-narrow linewidth atomic filters have developed rapidly. Turner et al. [21] described an atomic optical filter as a single 170 MHz passband at a peak transmission of 9.5% that used a narrow-linewidth pump laser to induce circular birefringence in a dense potassium vapor. Cerè et al. [22] achieved a tunable narrowband filter with a linewidth of 80 MHz, a peak transmission of 14.6% based on optical-pumping-induced circular dichroism in rubidium vapor. Liu et al. [23] reported an ultra-narrow bandwidth atomic filter with a linewidth of 61 MHz and

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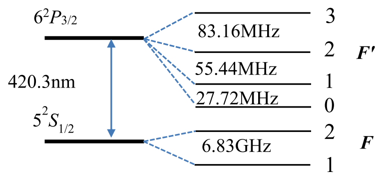

Fig. 1. Relevant hyperfine energy levels of ^{87}Rb.

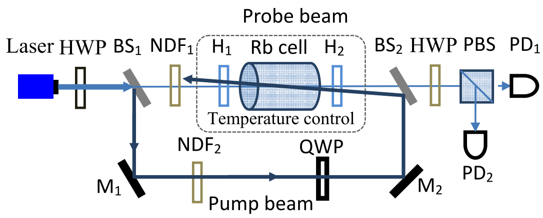

Fig. 2. Experimental schematic diagram of ^{87}Rb ultra-narrow linewidth atomic filter at 420 nm: Laser: 420 nm external cavity diode laser; HWP: half wave plate; $BS_{1,2}$: beam splitter; NDF: neutral density filter; $H_{1,2}$: permanent magnets; M: high reflection mirror; QWP: quarter-wave plate; PBS: polarized beam splitter; $PD_{1,2}$: photoelectric detector.

a peak transmission of 14.9% in rubidium vapor. Wang et al. [24] researched a nonlinear optical filter with a bandwidth of 6.2 MHz at 455 nm, and a peak transmission of 14.9% in cesium vapor. We recently reported a peak transmission of 98% with a bandwidth of 2.5 GHz at 420 nm, in which the temperature of the isotope ^{87}Rb cell was 280 °C and the magnetic field was 500 G [25].

In this study, we successfully make an ultra-narrow bandwidth atomic filter at 420 nm, narrowing the bandwidth from 2.5 GHz to about 15 MHz by adjusting the optical path and using the Faraday effect, circular dichroism, and saturated absorption.

2. Experimental

Fig. 1 shows the relevant hyperfine energy levels of ^{87}Rb. There are two hyperfine energy levels in the ground state $5S_{1/2}$, namely $F = 1$, $F = 2$ and the frequency interval is 6.83 GHz. There are four hyperfine energy levels in the excited state $6P_{3/2}$, namely $F' = 0$, $F' = 1$, $F' = 2$, $F' = 3$ and the corresponding frequency intervals are 27.72 MHz, 55.44 MHz, 83.16 MHz. Our 420 nm laser can be tuned to any of the $5S_{1/2}$, $F = 1 \rightarrow 6P_{3/2}$, $F' = 0,\ 1,\ 2$ transitions and $5S_{1/2}$, $F = 2 \rightarrow 6P_{3/2}$, $F' = 1,\ 2,\ 3$ transitions [26].

In this letter, we show that ultra-narrow atomic filter can be obtained by exploiting the joint action of the Faraday effect, laser-induced dichroism, and saturated absorption. Its principle is that the pump light makes atomic resonance excited states tend to saturation so that the Rb vapor is partially transparent to the probe light in these transition energy levels being absorbed completely. The polarization of the probe light experiences a certain degree rotation under the Faraday effect and laser-induced dichroism, which allows the probe to pass through the crossed polarizers. Using these methods, we can realize an ultra-narrow linewidth filter with bandwidth close to that of the saturated absorption spectrum.

Fig. 2 shows an experimental schematic diagram of the ^{87}Rb ultra-narrow linewidth atomic filter at 420 nm. The beam size of the laser is 3 mm × 1.5 mm. Linearly-polarized light emitted from an external-cavity semiconductor laser splits into two beams at beam splitter BS_1, with the stronger beam acting as the pump light and the weaker as the probe light. The intensities of the probe and pump beams can be controlled by neutral density filters (NDF_1 and NDF_2). The length of Rb cell is 5 cm, and it contains 3.5% ^{85}Rb and 96.5% ^{87}Rb.

After passing through the quarter-wave plate (QWP), the linearly polarized pump beam becomes circularly polarized and coincides with the probe beam after two reflections at M_1 and M_2 as well as the semitransparent prism BS_2. The pump beam plays two roles, firstly, the pump beam is strong enough to saturate the resonance level to produce a Doppler-free signal by atomic velocity-selection, and secondly, the pump beam is circularly polarized, thus producing laser induced dichroism. Inside the ^{87}Rb vapor cell, the linearly polarized probe beam, as a superposition of clockwise and counterclockwise circularly polarized light, is affected by the combination of magnetically induced dichroism and atomic velocity-selected laser induced dichroism. The difference between these two signals forms a dispersive Doppler-free signal. These methods have been separately discussed in depth in Refs. [21–24,27].

The half wave plate (HWP) near the laser is used to adjust the power of probe and pump light. By combining the second HWP and the polarized beam splitter (PBS), one can adjust the ratio between transmission and reflection on PD_1 and PD_2. One of the two beams emitted from the polarized beam splitter (PBS) is parallel to the polarization direction of probe beam and the other beam is perpendicular to the polarization direction of probe beam. The signal parallel to the polarization direction of probe beam is detected by the photoelectric detector PD_1, namely, the saturated absorption spectrum and is used as a reference signal for the ultra-narrow linewidth atomic filter. The signal perpendicular to the polarization direction of probe beam is received by the photoelectric detector PD_2 and is used for the signal of ultra-narrow linewidth atomic filter. The distance between two permanent magnets (H) can be adjusted to tailor the intensity of the magnetic field. Since the path of the laser in the Rb cell coincides with the center axis of the two permanent magnets, the magnetic field in the interactional area of the laser and the Rb atom can be considered as uniform. We measured the magnetic field at the center of two side surfaces of the cell and that of the cell internal center using a magnetometer. The measured magnetic field varies by less than 8.5% and the uniformity is better than 91.5%. A magnetic shielding device is used to reduce any external magnetic field [24].

The ^{87}Rb cell is wrapped in a heating film, using a thermistor to detect the change of cell temperature. The temperature is compared with a setpoint one, and thus the difference signal is obtained and processed by a PID circuit, which gives feedback to achieve temperature control. The thermistor is placed on the outer wall of the cell. We argue that the difference between the wall temperature and the internal temperature of the cell is less than 0.5 °C after a period of stabilization. The temperature of the ^{87}Rb cell can be adjusted continuously between room temperature and 150 °C with a stability of 0.1 °C, which meets the experimental requirements.

Although the Zeeman Effect is important for some applications, our experiment uses a relatively weak magnetic field (2–18 G). The influence of the magnetic field on the result, being proportional to the required linewidth of FADOF transmission, is small compared with a traditional FADOF with bandwidth of 1–2 GHz. The reason is discussed in depth Ref. [27].

The main mechanism of the magnetic field in the atomic optical filter is polarization rotation due to resonance-induced dispersion between the two circular polarizations. The filter bandwidth is 15 MHz, which is much narrower than Doppler width (∼2.5 GHz). Since velocity-selective optical pumping and elimination of the Doppler Effect lead to only a few low-velocity atoms being pumped into the excited state, the result is an ultra-narrow bandwidth FADOF.

3. Results and discussion

In the first experiment, the variations of transmission with the strength of magnetic field were measured, as shown in Fig. 3. The temperature of cell, the pump power and the probe power are set