Ultranarrow Bandwidth Optical Filter Based on Laser Cooled ^{87}Rb Atoms

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***Abstract*—We propose and implement two ultranarrow-bandwidth optical filters with different principles based on laser-cooled ^{87}Rb atoms. Using the cold atomic cloud trapped in magneto-optical trap (MOT) to replace the vapor cell of traditional Faraday anomalous dispersion optical filter (FADOF), the effect of Doppler broadening on the transmitted bandwidth of FADOF will be effectively suppressed to the order of natural linewidth. Thus, an ultranarrow-bandwidth FADOF with a bandwidth of 2.7(2) MHz and a peak transmission of 3.2% is realized. It is the narrowest bandwidth FADOF known at present. Moreover, a transmission-enhancing method based on optical pumping is proposed. The two circularly polarized components of a linearly polarized probe laser have a large refractive index difference (induced dichroism), when it goes through the unidirectional population of atoms. Thus, forming a large rotation angle with high transmission. The two schemes can be extended to almost all kinds of atomic optical filters and may find applications in active optical frequency standard and self-stabilizing laser.**

***Keywords*—optical filter; ultranarrow-bandwidth; cold atom; optical pumping; induced dichroism.**

I. INTRODUCTION

Atomic optical filter with advantages of high peak transmission [1-3], narrow bandwidth [4-6], and excellent out-of-band rejection [7], has been widely studied in theory and experiment. Recently, ultranarrow-bandwidth atomic filters are particularly promoting [8-11]. However, it is difficult to narrow the transmitted bandwidth of atomic filter to the order of natural linewidth, considering the Doppler broadening induced by the thermal atomic ensemble.

Cold atoms can overcome the Doppler effect caused by atomic motion and other atomic velocity related factors in the process of interaction between light and atoms. In this work, we innovatively combine cold atoms with Faraday anomalous dispersion optical filter (FADOF). By using laser cooling technology to slow down atoms, so as to reduce the influence of Doppler effect, we demonstrate an ultranarrow-bandwidth FADOF operating on the ^{87}Rb $5^2S_{1/2}$ (F=2) - $6^2P_{3/2}$ (F'=3) transition at 420 nm. The filter achieves a single 2.7(2) MHz passband at a peak transmission of 3.2%. It is the narrowest bandwidth FADOF known at present.

After narrowing the transmitted bandwidth of FADOF, considering that in the FADOF realized by thermal-atom scheme, the number of atoms in the vapor cell can reach 10^{12}, while in the FADOF realized by cold-atom scheme, the number of cold atoms trapped by laser cooling technology is only about 10^8. Although the density of the two gas atoms is approximately the same, the length of laser traveling in the cold atom medium is much shorter than that of the thermal atom. The decrease in the number of atoms interacting with the laser is detrimental to the atomic optical filter's transmission. Therefore, this work innovatively proposes to improve the transmission of cold-atom optical filter by optical pumping technology. Experimental results show that, under the same transition, the peak transmission of our achieved cold-atom optical filter (15.6%) is nearly 14 times higher than that of the cold-atom optical filter realized by Faraday magneto-optic effect (1.14%).

II. METHODS/RESULTS

Here, the schemes of ultranarrow-bandwidth cold-atom FADOF, and cold-atom optical filter enhanced by optical pumping are proposed, respectively.

Figure 1 depicts the energy level and the working schematic of the ultranarrow-bandwidth cold-atom FADOF. The cold ^{87}Rb atoms are prepared by a standard 3D magneto-optical trap (MOT) [12]. There are around 2×10^8 atoms trapped with a temperature of around 200 μK. The diameter of the cold atomic cloud is about 2 mm, the density of the cold atomic vapor is about 10^{10}/cm^3. Then, locking the 420 nm probe laser to $5^2S_{1/2}$ (F=2) - $6^2P_{3/2}$ (F'=3) transition, and letting it pass through a neutral density filter (NDF), a Glan-Taylor prism (GT), and the cold atomic cloud trapped in the vacuum system, then turned back by a total reflection mirror (M). Here, the double-pass probe method can reduce the force generated by the probe laser on cold atomic cloud. The diameter of the probe laser beam is about 1 mm. The transmitted signal of FADOF is received by a photo-electric detector (PD) at the other end of GT. The homogeneous magnetic field along the probe laser direction is generated by a pair of energized coils.

In order to avoid the interaction between the gradient magnetic field (MOT) and the homogeneous magnetic field (FADOF), we set 2 s as a cycle, the MOT is switched off at 1.5 s, then immediately turn on the probe laser and homogeneous magnetic field to measure the FADOF's transmitted signal. Under the experimental conditions of the probe laser power 10 μW, and the homogeneous magnetic field 3 G, we use two acousto-optic modulators (AOMs) to generate frequency detuning near the probe laser resonance frequency, discretely measure the transmission values at multiple frequency points, and then draw them in combination. Thus, the transmission spectrum of the cold-atom FADOF is obtained (see the black points in Fig. 2), the error bars are given by 20 cycles of measurements. Using Lorentz fitting (red curve), it can be concluded that the transmitted bandwidth of FADOF realized in this study is 2.7(2) MHz, and the peak transmission is 3.2%. It is the narrowest bandwidth FADOF known at present.

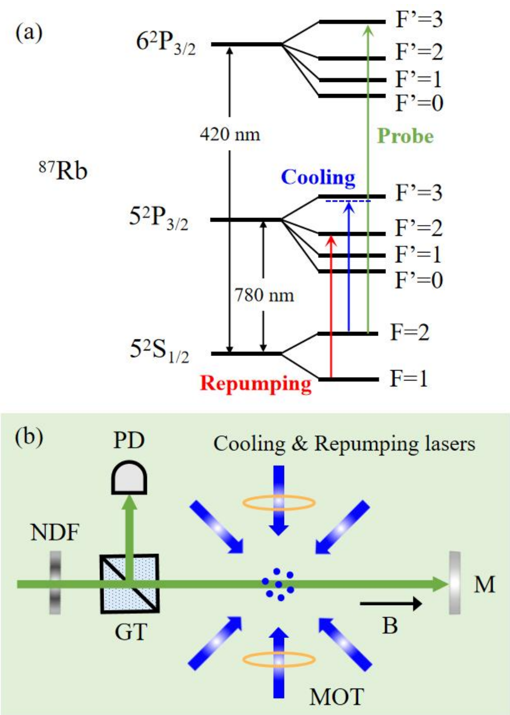

Fig. 1. Energy-level diagram and the working schematic of the ultranarrow-bandwidth cold-atom FADOF. (a) The cooling laser has a red detuning of 15 MHz to the transition frequency of $5^2S_{1/2}$ (F=2) - $5^2P_{3/2}$ (F'=3). (b) NDF: neutral density filter; GT: Glan-Taylor prism; M: mirror with reflectivity of 100%; PD: photo-electric detector; MOT: magneto-optical trap.

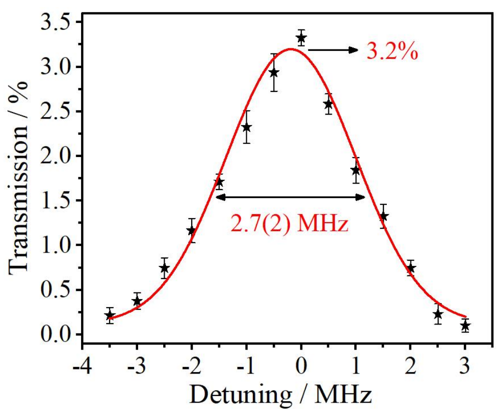

Fig. 2. Transmission spectrum of the cold-atom FADOF (corresponding to $5^2S_{1/2}$ (F=2) - $6^2P_{3/2}$ (F'=3) transition).

Figure 3 depicts the energy level and the working schematic of the cold-atom optical filter enhanced by optical pumping. The preparation of cold atoms is the same as Scheme I. The 780 nm probe laser locked to $5^2S_{1/2}$ (F=2) - $5^2P_{3/2}$ (F'=2) transition is firstly transmitted to the NDF to adjust the laser power. Then, it passes through the cold atomic cloud trapped in the vacuum system, a pair of GTs with orthogonal polarization direction, and then enters the PD, which measures the transmitted signal of the cold-atom optical filter. On the other side, a beam adjusted to the $5^2S_{1/2}$ (F=2) - $5^2P_{3/2}$ (F'=2) transition is used as the pump laser for this study. It passes through a half-wave plate (HWP), a polarizing beam splitter (PBS), a pair of plane-convex lenses (L1 and L2), and a quarter-wave plate (QWP), then reflected by a mirror with reflectivity of 10% and transmission of 90% (M'). The reflected pump laser overlaps with the probe laser in reverse and passes through the cold atomic cloud trapped in the vacuum system. Here, HWP and PBS are used to adjust the pump laser power and turn the pump laser into a pure linearly polarized light. L1 and L2 are used to expand the pump laser beam. QWP is used to convert the linearly polarized pump laser into a standard σ^+ circularly polarized pump laser.

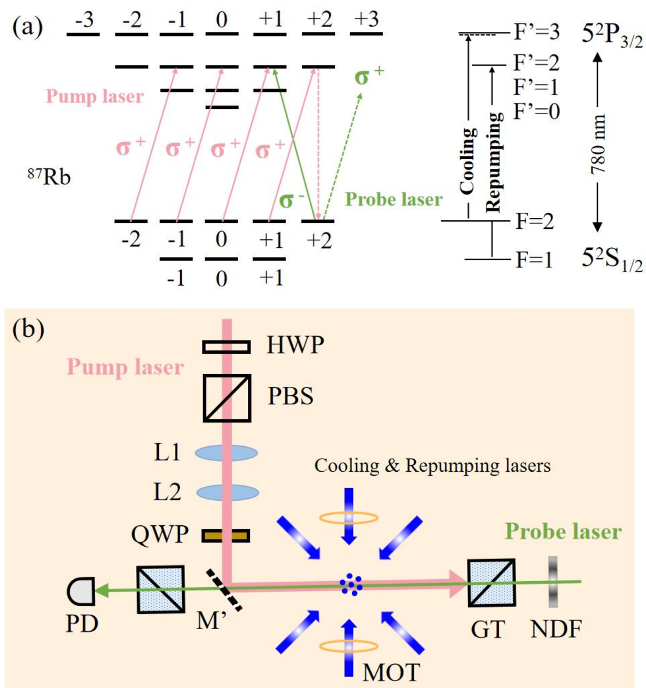

Fig. 3. Energy-level diagram and the working schematic of the cold-atom optical filter enhanced by optical pumping. (a) The cooling laser has a red detuning of 15 MHz to the transition frequency of $5^2S_{1/2}$ (F=2) - $5^2P_{3/2}$ (F'=3). (b) NDF: neutral density filter; GT: Glan-Taylor prism; PD: photo-electric detector; HWP: half-wave plate; PBS: polarizing beam splitter; L1 and L2: plane-convex lenses; QWP: quarter-wave plate; M': mirror with reflectivity of 10% and transmission of 90%; MOT: magneto-optical trap.

According to the selection rule: $\Delta m_F = m_{F'} - m_F = +1$, the σ^+ circularly polarized pump laser gradually pumps atoms from low magnetic sublevels to high magnetic sublevels, resulting in an accumulation of population on $5^2S_{1/2}$ (F=2, m_F = +2). Due to the asymmetry, only the σ^- circularly polarized light component in the linearly polarized probe laser can be absorbed, while the other one is almost not, the large difference in refractive indices forming a large rotation angle of the optical filter, thus the transmission is enhanced.

Specifically, we set 2 s as a cycle, the MOT is switched off at 1.5 s (keep the repumping laser on at all times). Then, after a time interval of 1 ms, turn off the pump laser (0 s - 1.501 s) and immediately turn on the probe laser to measure the transmitted signal of the cold-atom optical filter. Under the experimental conditions of the probe laser power 3 μW, the probe laser beam diameter 1 mm, the pump laser power 1.5 mW, and the pump laser beam diameter 8 mm, we use AOMs to measure the transmission spectrum of the cold-atom optical filter which operates on the $5^2S_{1/2}$ (F=2) - $5^2P_{3/2}$ (F'=2) transition, the measurement results are shown as the black points in Fig. 4. Using Lorentz fitting (red curve), it can be concluded that the transmitted bandwidth of the cold-atom optical filter realized by optical pumping method is 6.6(4) MHz, and the peak transmission is 15.6%.

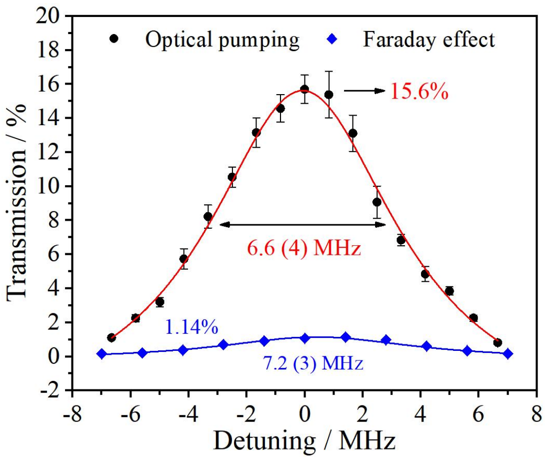

Fig. 4. Transmission spectrum of the cold-atom optical filter (corresponding to $5^2S_{1/2}$ (F=2) - $5^2P_{3/2}$ (F' =2) transition). Each point is obtained by averaging 20 measurements.

Referring to Scheme I, we also measure the transmission spectrum of the cold-atom optical filter realized by Faraday magneto-optical effect under the same transition (F=2 - F'= 2), seeing the blue points in Fig. 4. From the comparison, it can be clearly seen that the cold-atom optical filters implemented by the two different schemes all have an ultranarrow bandwidth close to the natural linewidth (6.1 MHz) of atomic transition. However, the peak transmission of the cold-atom optical filter realized by optical pumping method is nearly 14 times higher than that of the cold-atom optical filter realized by Faraday magneto-optical effect.

III. DISCUSSION

These experimental schemes are also applicable to other alkali-metal atoms, such as Cs. The transmission of cold-atom optical filter can be further improved by increasing the optical thickness (OD), which is specifically influenced by the density of gas atoms and the length of atomic medium [13]. An ultranarrow-bandwidth filter with high transmission might reveal active optical frequency standard without an additional locked pump laser [14]. Furthermore, trapping atoms in MOT on chip [15] can expand optical frequency standard's applications in the future, for its less cost and complexity. And the problem of cold-atom filter operating in pulse mode may be solved by using optical molasses to prepare cold atoms.

IV. CONCLUSIONS

In conclusion, to reduce the Doppler broadening induced by the thermal atomic ensemble, this work proposed an ultranarrow bandwidth FADOF implementation scheme based on laser cooled ^{87}Rb atoms. To our knowledge, it is for the first time that cold atoms are combined with FADOF. Moreover, this work also proposed a transmission enhancing method based on optical pumping, which greatly increase the peak transmission of ultranarrow-bandwidth cold-atom optical filter. In the future, such an ultranarrow-bandwidth optical filter may have applications in self-stabilizing laser, and active optical clock. And the two schemes we proposed can be extended to almost all kinds of atomic optical filters.

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