# Atomic filter based on stimulated Raman transition at the rubidium D1 line

**Xiuchao Zhao,[1,2] Xianping Sun,[1,3] Maohua Zhu,[1] Xiaofei Wang,[1,2] Chaohui Ye,[1] and Xin Zhou[1,*]**

[1]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China*
[2]*University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*xpsun@wipm.ac.cn*
[*]*xinzhou@wipm.ac.cn*

**Abstract:** We report on a 795 nm atomic filter consisting of a stimulated Raman gain amplifier together with normal Faraday anomalous dispersion optical filtering (FADOF) at the rubidium D1 line. The filter is operated with a single transmission peak. The gain of the filter's transmission light signal is enhanced up to 85-fold compared to case operating without a stimulated Raman transition. Based on atomic coherence, the filter's minimum transmission bandwidth is less than 22 MHz. In each filtering channel, the signal light's frequency can be tuned by changing the detuning of the coupling light. Such a filter with stimulated Raman gain is more efficient in extracting weak signals in the presence of a strong light background compared with the normal FADOF. This expands the range of potential applications in optical communications and lidar technology. This filtering method can also be extended to the lines of other atoms.



**OCIS codes:** (230.2240) Faraday effect; (120.2440) Filters; (300.6210) Spectroscopy, atomic; (060.4510) Optical communications.

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## 1. Introduction

FADOF spectral filtering devices play a key role in the detection of weak signals, due to their narrow transmission bandwidths of GHz, high out-of-band background light noise extinction ratios (~$10^5$:1), adjustability of transmission peak frequency, and imaging capabilities among many features [1–3]. FADOFs utilizing alkali atom vapors generally operate on atomic transition lines between the ground state (S) and the excited state (P) [2–6]. Some excited state FADOFs [7–9] have been studied involving atomic transitions between excited P and excited S or D states. Here, FADOFs provide multiple dispersive modes of operation at the line center or the wings of the atomic resonance [4–6]. However, conventional FADOFs are unable to achieve light gain or amplification of weak signals. For systems operated during daytime, such as long-distance free-space optical communications (laser or quantum [10,11]) and lidar technology [12–14], it is necessary to improve the signal transmission of FADOFs to more effectively extract the weak light signals and decrease the error rate induced by background light noise.

Certain light amplification schemes, such as light amplification without inversion in any standard state basis, light amplification by stimulated Raman scattering, and light amplification from population inversion in the dressed states, have been analyzed and realized experimentally [15–17]. In particular, Zhu [16] systematically analyzed light amplification mechanisms in a coherently coupled atomic system. The gain or amplification of signal light is one possible way in which FADOFs can be improved [15,18].

In this article, we experimentally studied the transmission peak feature of a 795 nm atomic filter based on stimulated Raman transition at the rubidium D1 line. We found that this atomic filter with stimulated Raman gain operates with a single transmission peak. Transmission light signal of the atomic filter with stimulated Raman gain can be enhanced up to 85-fold over the one without the coupling light, and the minimum transmission bandwidth is less than 22 MHz owing to the stimulated Raman transition. The atomic filter based on stimulated Raman transition is able to provide more efficient filtering in some applications.

## 2. Experimental schematics

The schematic diagram of the experiment is shown in Fig. 1. The atomic cells with glass windows are filled with naturally abundant rubidium (rubidium-85: 72.2% and rubidium-87: 27.8%). Cell 1 provides the Raman gain and cell 3 provides Faraday rotation of the signal light at the rubidium D1 line. In order to produce enough rubidium atom vapor for the processes of stimulated Raman and Faraday rotation, the temperatures of cell 1 (20 mm diameter and 100 mm length) and cell 3 (20 mm diameter and 50 mm length) are maintained by electric heaters and kept at 353 K using a home-built PID controller. Cell 2 (20 mm diameter and 100 mm length) is kept at ambient temperature and provides the reference atomic absorption signal.

A strong laser (laser 1) from a Toptica TA pro 795 laser is used both as a coupling light and as a pumping light. A second but weak laser (laser 2) generated by a Toptica DL 100

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laser serves as a signal light. The beam diameters of the coupling and signal lights are shaped to 1.5 mm and 1 mm, respectively. The lasers are all operated at 795 nm. The powers of the vertically polarized coupling light and horizontally polarized signal light are ~mW and ~μW, respectively. The lights pass through PBS (polarizing beam splitter) 2 and overlap with a small angle in cell 1. PBS 3 behind rubidium cell 1 is used to prevent the coupling light from passing through cell 3. The stimulated Raman gain process utilized in cell 1 can be described with the rubidium-85 detuned three-level Λ system at the D1 line (Fig. 2). The frequency of laser 1 can be tuned near the $5^2\mathrm{S}_{1/2}, \mathrm{F}=3 \rightarrow 5^2\mathrm{P}_{1/2}, \mathrm{F}'=2,3$ transition of rubidium atoms, so it can optically pump the atoms in the level $5^2\mathrm{S}_{1/2}, \mathrm{F}=3$ to the level $5^2\mathrm{S}_{1/2}, \mathrm{F}=2$, creating a population difference between the two ground states. It also creates coherence between the two ground states by interacting via the transition $5^2\mathrm{S}_{1/2}, \mathrm{F}=2 \rightarrow 5^2\mathrm{P}_{1/2}, \mathrm{F}'=2,3$ as coupling light. $\Delta_1$ and $\Delta_2$ are the detuning for coupling and signal lights, respectively. When adjusting the detuning $\Delta_1$, the detuning $\Delta_2$ is also altered. The optical pumping and the coherence jointly generate a Raman gain for signal light. The Raman process can be described by the density matrix equations as follows [19]:

$$
\begin{aligned}
&\frac{d\rho_{11}}{dt} = \Lambda(\rho_{33}-\rho_{11}) + i\Omega_{31}(\rho_{31}-\rho_{13}) + \gamma_{31}\rho_{33},\\
&\frac{d\rho_{22}}{dt} = i\Omega_{32}(\rho_{32}-\rho_{23}) + \gamma_{32}\rho_{33},\\
&\frac{d\rho_{33}}{dt} = \Lambda(\rho_{11}-\rho_{33}) + i\Omega_{31}(\rho_{31}-\rho_{13}) + i\Omega_{32}(\rho_{32}-\rho_{23}) - (\gamma_{31}+\gamma_{32})\rho_{33},\\
&\frac{d\rho_{12}}{dt} = -\left(\frac{\Lambda}{2} + i(\Delta_2-\Delta_1)\right)\rho_{12} - i\Omega_{32}\rho_{13} + i\Omega_{31}\rho_{32},\\
&\frac{d\rho_{13}}{dt} = -\left(\frac{\gamma_{31}+\gamma_{32}}{2} + \Lambda + i\Delta_2\right)\rho_{13} - i\Omega_{32}\rho_{12} + i\Omega_{31}(\rho_{33}-\rho_{11}),\\
&\frac{d\rho_{23}}{dt} = -\left(\frac{\Lambda+\gamma_{31}+\gamma_{32}}{2} + i\Delta_1\right)\rho_{23} - i\Omega_{31}\rho_{21} + i\Omega_{32}(\rho_{33}-\rho_{22}),\\
&\rho_{11}+\rho_{22}+\rho_{33} = 1.
\end{aligned} \tag{1}
$$

$\rho_{11}$, $\rho_{22}$, and $\rho_{33}$ are the populations of the $5^2\mathrm{S}_{1/2}, \mathrm{F}=3, \mathrm{F}=2$ and excited state $5^2\mathrm{P}_{1/2}$, respectively. $\Lambda$ is the pumping rate. $\Omega_{32}$ is the coupling light Rabi frequency. $\Omega_{31}$ is the probe light Rabi frequency. $\gamma_{31}(\gamma_{32})$ is the spontaneous decay rate from excited state to $5^2\mathrm{S}_{1/2}, \mathrm{F}=3, \mathrm{F}=2$.

Solving the above equations in the steady state yields

$$\rho_{13} = 2i\frac{\Omega_{31}(\rho_{33}-\rho_{11}) - \Omega_{32}\rho_{12}}{2\Lambda + \gamma_{31} + \gamma_{32}}. \tag{2}$$

The signal gain is proportional to the imaginary part of $\rho_{13}$. The signal light with stimulated Raman gain then passes through the normal FADOF consisting of two orthogonal Glan-Taylor polarizers P1 and P2 (with extinction ratios $10^6$:1) and cell 3 located in a 20 mT magnetic field generated by a pair of permanent magnets. Because cell 3 provides a Faraday rotation, and the frequency of the signal light is tuned to within one filtering channel of the normal FADOF, the background light noise and the remaining coupling light are filtered. Therefore, an atomic filter with stimulated Raman gain can be achieved. The transmission coefficient of the FADOF is given by

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$$T=\frac{1}{2}G\cdot e^{-\mathrm{Im}(k_{+}+k_{-})L}\left\{\cos\mathrm{h}\left[\mathrm{Im}\left(k_{+}+k_{-}\right)L\right]-\cos\left[\mathrm{Re}\left(k_{+}-k_{-}\right)L\right]\right\}. \tag{3}$$

where $L$ is the length of the filter cell 3, $G$ is the gain coefficient, and $k_{\pm}$ is the circular wave number.

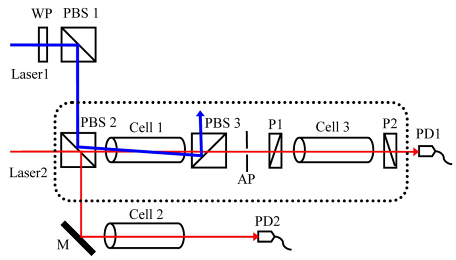


Fig. 1. Schematic diagram of the experimental apparatus: Laser 1, emitted from a Toptica TA pro laser at 795 nm, is used to provide the coupling and pumping lights. Laser 2, emitted from a Toptica DL 100 laser at 795 nm, provides the signal light. The two lasers are overlapped with a small angle in cell 1, and an aperture (AP) is set behind PBS 3 to further eliminate the slight coupling light. PBS 1, 2, and 3 are polarizing beam splitters. Cells 1, 2, and 3 stand for rubidium atom cells 1, 2, and 3, respectively. M stands for mirror. P1 and P2 are Glan-Taylor polarizers 1 and 2, respectively. PD1 and PD2 are photoelectric detectors.

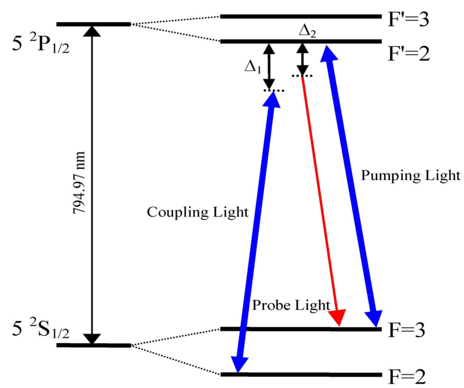


Fig. 2. Rubidium-85 detuned three-level $\Lambda$ - type scheme.

## 3. Experimental results

Figure 3 shows a typical transmission spectrum of the atomic filter with stimulated Raman gain in rubidium at 795 nm. The powers of the coupling light and the signal light are 139 mW and 280 μW, respectively. The inset is the normal transmission spectrum of the rubidium 795 nm FADOF without the coupling light. From the inset, we find that normal FADOF has a filtering channel at 5.4 GHz detuning from the $5^2S_{1/2}, F{=}2 \rightarrow 5^2P_{1/2}, F'{=}2$ transition of rubidium-85. We can then adjust the frequency of the coupling light to match this detuning frequency and obtain the transmission signal with stimulated Raman gain. As an example, calibration by the reference absorption spectrum of the rubidium atoms gives that the transmission peak bandwidth of the atomic filter with stimulated Raman gain is approximately 22 MHz. The Raman-gain factor of the atomic filter, typically about 16 in this situation, can be obtained by calculating the ratio of the amplified transmission to the corresponding transmission without amplification.

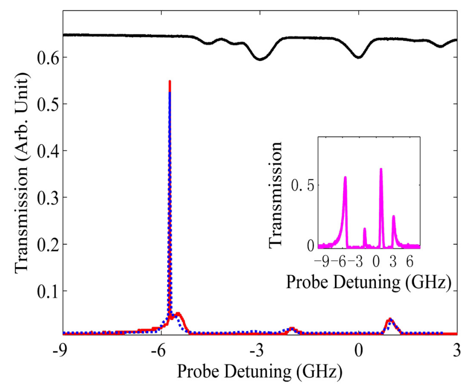


Fig. 3. Typical Raman-gain transmission spectrum with the coupling light. Fit to the theory is shown by a dashed blue curve. The black curve is the reference absorption signal detected from cell 2 for identification of the detuning. The red curve is obtained when $\Delta_1$ = 3 GHz corresponds to the transmission bandwidths of the normal FADOF depicted in the inset. The left filtering channel of the normal FADOF has a bandwidth of approximately 650 MHz.

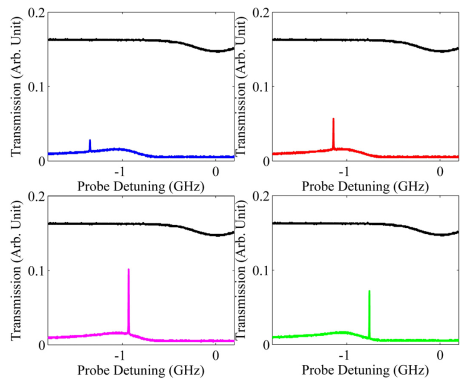


Fig. 4. The transmission spectra of the atomic filter with stimulated Raman gain versus different detuning coupling lights. The black absorption curves correspond to the transition Rubidium-87 $5^2S_{1/2}$, F=2 $\rightarrow$ $5^2P_{1/2}$, $F'$=1 .

By continuously adjusting the frequency of the coupling light, the corresponding signal light with stimulated Raman gain can be observed in a filtering channel of the normal FADOF. As shown in Fig. 4, there are four transmission peaks of the atomic filter corresponding to different frequencies of the coupling light. It is shown that the frequency of the transmission peak is adjustable in the channel. The amplifications of the four transmissions are different due to the different frequencies of the coupling light. It is shown that because the coupling light possesses two modes of interaction in the stimulated Raman transition (optical pumping and coupling to the corresponding transition of atomic levels), the factor of Raman gain of the atomic filter changes with coupling light frequency. Under our experimental condition, the transmission spectra show a maximal Raman gain factor at the coupling light detuning frequency of 3.5 GHz.

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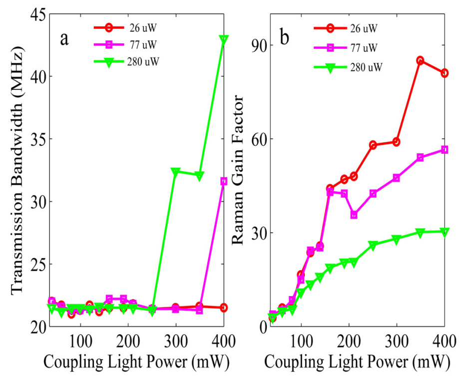


Fig. 5. Transmission bandwidth (a) and Raman-gain factor (b) of the signal light with different coupling light power. The curves are obtained when the signal light power was set to 26 μW, 77 μW, and 280 μW, respectively. Detuning of the coupling light is the same as that in Fig. 3.

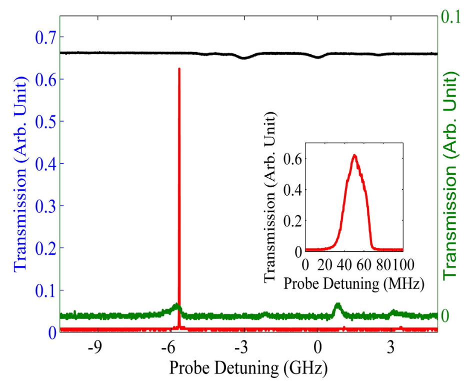


Fig. 6. The 85-fold enhancement transmission spectrum is obtained with 22 MHz bandwidth shown in the inset. The green line presents the transmission without Raman gain. The inset shows the bandwidth of the enhancement transmission spectrum by the calibration of the rubidium atomic absorption peaks (black).

As shown in Fig. 5, the bandwidths of the transmission spectra based on the stimulated Raman transition remain <22 MHz when the signal light power is 26 μW [17]. The transmission spectra show a maximal Raman gain factor of 85 shown in Fig. 6 when the coupling light power is 350 mW. Moreover, we also can change the powers of the coupling light and the signal light to realize different Raman gain factors of the transmission peaks. Although the bandwidths of the transmission spectra became bigger for probe light powers of 77 μW and 280 μW, they are narrower than the bandwidth of the normal FADOF. The Raman-gain factors are increased and not saturated for this choice of experimental parameters.

As shown in Fig. 7, the atomic filter with stimulated Raman gain at 795 nm can provide a single transmission channel for different frequencies of the light signals. When we adjust the detuning frequency of the coupling light, the transmission peaks with stimulated Raman gain can be obtained in the filtering channels of the normal FADOF. This means that this filter can work not only in single channel mode but also in the other filtering channels. Similarly, the frequency of the transmission peak is also adjustable in the other channels. The working temperatures of cells 1 and 3 are always kept at 353 K in these experiments.

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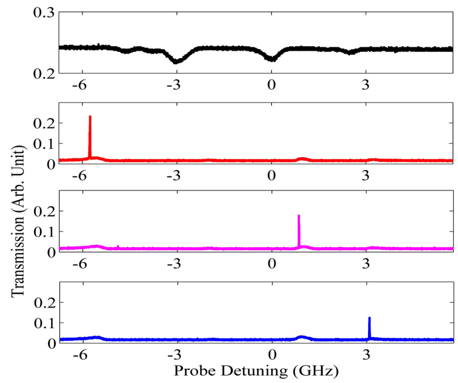


Fig. 7. The transmission spectra of the atomic filter based on the simulated Raman transitions, which work with the related filtering channels of the normal FADOF. The powers of the coupling light and signal light are 180 mW and 210 μW, respectively.

## 4. Conclusion

In conclusion, we have described an experimental setup and the fundamental physical principles of an atomic filter based on stimulated Raman transition at the rubidium D1 line. By comparison, the atomic filter with stimulated Raman gain has several transmission characteristics. First, this atomic filter can operate in a single transmission channel. The normal FADOF has multiple channels, i.e., when one of the channels is used as a signal transmission channel, the other channels become noisy. Second, when we change the frequency of the coupled light, the atomic filter with stimulated Raman gain can be adjusted to a different single transmission channel. Third, the transmission signals of the atomic filter are enhanced. Under our experimental conditions, a maximum signal gain of 85 times was achieved at a comparable light intensity when the coupling laser was turned on and off. Fourth, owing to atomic coherence, the atomic filter with stimulated Raman gain has an ultra-narrow transmission bandwidth <22 MHz at a probe light power of 26 μW. The Raman-gain factor and the frequency of the transmission can be changed by adjusting some parameters. For example, the power or the frequency of the coupling light and the signal light. Therefore, this atomic filter with stimulated Raman gain could find applications in optical communication (laser or quantum), lidar detection and other applications where suppression of the background noise is important. This filter method can also be extended to lines of other atoms.


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