A 780 nm Voigt laser inherently corresponding to atomic transition line

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***Abstract*—The development of laser sources capable of automatically aligning with atomic spectral lines is crucial for the creation of plug-and-play atomic devices, such as optical clocks and atomic gravimeters, with an enhanced adaptability to environmental conditions and operational efficiency. A Voigt laser, realized in 2023, has achieved the functionality of consistently aligning with the target frequency regardless of laser parameters. However, this frequency still exhibits a discrepancy from the atomic transition line, necessitating an additional electro-optic modulator (EOM) for frequency calibration in practical applications, which increases system complexity. To address this issue, we conducted an in-depth study of the parameters and frequency selection mechanism of the Voigt laser's internal frequency selection element: the Voigt anomalous dispersion optical filter (VADOF). By optimizing the VADOF parameters, we achieved alignment with the atomic transition line while ensuring sufficiently high transmission of the atomic filter. Based on this, we developed a Voigt laser with the inherent capability of automatically aligning with atomic transition lines. The output laser wavelength is immune to temperature and current fluctuations in laser, remaining within 1.4 pm around the atomic transition line. This laser will have a highly positive impact on the advancement of atomic physics experiments and the industrialization of related devices.**

Keywords—atomic filter, atomic filter laser, Voigt anomalous dispersion optical filter, Voigt laser.

I. Introduction

Currently, high-precision atomic devices such as optical clocks and atomic gravimeters are widely applied in atomic physics and fundamental physics validations, leading to significant breakthroughs [1,2]. However, the complexity, immobility, and need for manual maintenance of laboratory-based atomic devices limit their applications across various fields. To address this issue, it is necessary to reduce the volume of atomic devices and realize a plug-and-play functionality.

One of the main reasons for requiring manual adjustment in atomic devices is that the laser sources used in the system tend to drift from the target working frequency due to external disturbances such as temperature and vibration over long-term operation, necessitating manual correction. This problem can be resolved by using the atomic filter laser as the laser source [3-5]. This laser employs an atomic filter as the frequency-selecting device, ensuring that the output laser frequency automatically aligns with the atomic transition frequency, unaffected by diode current and temperature of the laser diode.

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Atomic filter lasers are categorized into two types based on different atomic filtering principles: Faraday lasers [3,4]and Voigt lasers [5], both capable of achieving the aforementioned plug-and-play functionality. However, Voigt lasers have potential advantages in miniaturization. Since the atomic filter concept was proposed in 1956 [6], there have been few reports on Voigt atomic filters, and Voigt lasers were realized for the first time in 2023 [5]. Despite their superior interference resistance and frequency stability, Voigt lasers cannot automatically align with atomic spectral lines. Therefore, a detailed study of the Voigt atomic filter in Voigt lasers is imperative to optimize its transmission spectrum, ensuring that the highest transmission peak aligns with the atomic transition spectral line.

II. Method

In this study, we present an atomic filter laser that inherently correspond to the transition line of ^{85}Rb atoms by employing a Voigt anomalous dispersion optical filter (VADOF) as the frequency-selective element, named as "Voigt laser". Through detailed analysis of the main factors influencing the transmission spectrum of the VADOF, we selected the optimal parameters to align the highest transmission peak of the transmission spectrum with the ^{85}Rb cycling transition $5^2S_{1/2}$, F=3→$5^2P_{3/2}$, F=4. This

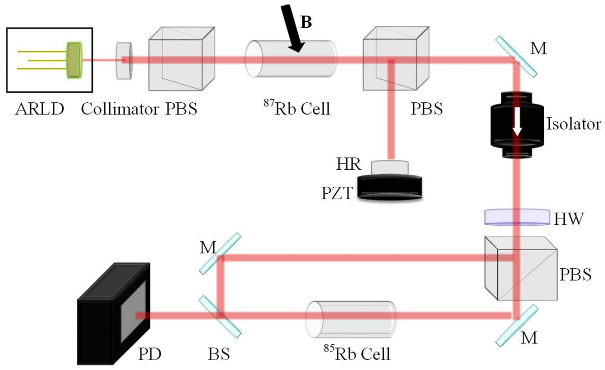

Fig. 1. Experiment setup of Voigt laser and saturated absorption spectrum detection optical path. ARLD, anti-reflection coated laser diode; PBS, polarizing beam splitter; HR, high-reflection mirror; PZT, piezoelectric transducer; PD, photon detector; HW, half-wave plate; EOM, electro-optic modulator; BS, beam splitter.

optimization resulted in a Voigt laser with the best performance. Similar to semiconductor lasers utilizing Faraday anomalous dispersion atomic filters for frequency selection, the Voigt laser's output frequency is confined within the 1 GHz bandwidth range of the atomic filter and consistently matches the atomic transition line. Importantly, these lasers exhibit exceptional resistant against variations in diode current and temperature, enabling they to maintain alignment with the atomic transition line during long-term operation without human intervention. This innovative laser will significantly contribute to realizing portable and ready-to-use high-precision atomic devices.

The setup of the Voigt laser operating on the ^{85}Rb 780 nm transition is depicted in Fig. 1. The Voigt laser is composed of a VADOF, an anti-reflection coated laser diode (ARLD), collimator, a high-reflectivity mirror (HR) and a piezoelectric ceramic tube (PZT). VADOF comprises an ^{87}Rb cell with a length of L = 30 mm, a set of permanent magnets, and two polarized beam splitters (PBSs). The light, after being excited by the diode, is collimated by a collimating lens, producing a Gaussian beam with a diameter of 1 mm. The collimated light then passes through the first polarizing beam splitter (PBS), allowing only P-polarized light to pass through. As the collimated light passes through a 30 mm long ^{87}Rb atomic vapor cell, the interaction between the rubidium atoms and the magnetic field causes the light polarization direction to rotate by 90 degrees, changing it to S-polarization. This S-polarized light is then reflected at the second PBS, directed into a high-reflectivity mirror (HR) mounted on a piezoelectric ceramic (PZT). Finally, the light returns along the original path, enabling the laser to oscillate. Evidently, only light with a frequency near the atomic spectral line can pass through the VADOF to form a laser. Therefore, the output frequency of the Voigt laser must remain near the atomic transition line. The output Voigt laser passes through the optical isolator (ISO) to block optical feedback and then is divided into two beams by a half-wave plate (HW) and a PBS. The reflected beam is used as the pump laser, and the transmitted beam is the probe laser. In this case, a saturated absorption spectrum (SAS) is obtained through tuning the frequency of the Voigt laser to visually evaluate whether the Voigt laser can align with the atomic transition line.

III. Result

Before constructing the Voigt laser, it is essential to conduct a detailed evaluation of the VADOF parameters to select the most suitable VADOF for application. Previous research indicates that VADOFs with smaller magnetic fields can align more easily with atomic transition lines, but they exhibit low transmission under high light intensity [5]. This makes it difficult for the constructed Voigt laser to oscillate and results in unstable output. Therefore, a larger magnetic field is required to ensure high transmission for VADOF under high light intensity. After multiple experimental tests and considering factors such as transmission, alignment with atomic transition lines, and the size of the magnets, we have chosen a magnetic field strength of 3700 G.

After determining the magnetic field, temperature and light intensity are the two most critical parameters affecting the transmission spectrum of the VADOF. First, we

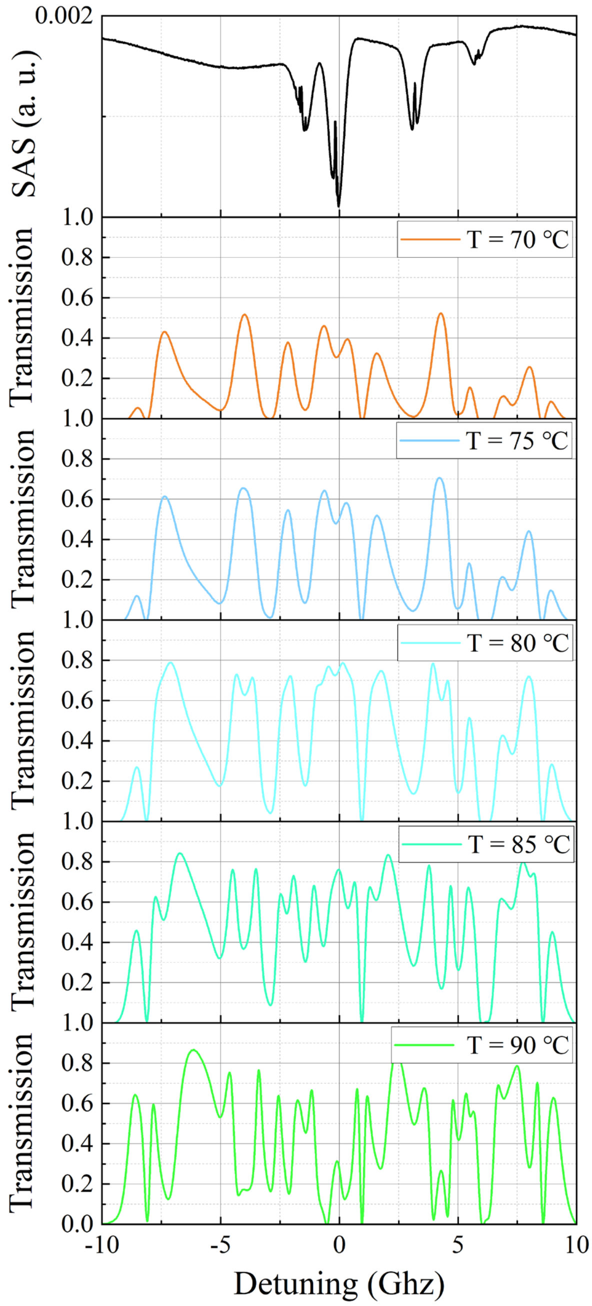

Fig. 2. Transmission spectrum of VADOF at different temperature. The figure at top presents the saturated absorption spectrum of Rb

extensively adjust the temperature of the atomic cell in the VADOF to determine the temperature range in which the transmission spectrum corresponds to the atomic transition line. Then, we finely tune the temperature of the atomic cell to align its peak transmission point as closely as possible with the target atomic transition line $5^2S_{1/2}$, F=3⟶$5^2P_{3/2}$, F=4. At this temperature, we vary the light intensity of the test laser to assess the VADOF's performance within the laser system, ultimately determining whether these parameters are suitable for constructing the Voigt laser.

The variation of the VADOF transmission spectrum with temperature is shown in Fig. 2. At 70°C, the transmission is relatively low, making it unlikely for a Voigt laser constructed with this parameter to oscillate. As the temperature is increased to 75°C, the shape of the transmission spectrum remains unchanged, but the transmission further improves. Continuing to increase the temperature to 80°C, the transmission approaches the limit of VADOF's transmission capability. Further temperature increases do not affect the maximum transmission but significantly impact the shape of the transmission spectrum. Notably, at this temperature, a transmission peak begins to appear near the frequency corresponding to the atomic transition line $5^2S_{1/2}$, F=3→$5^2P_{3/2}$, F=4, indicating the potential for aligning the transmission peak with the atomic spectral line. As the temperature continues to rise, the transmission peak aligned with the transition line $5^2S_{1/2}$, F=3→$5^2P_{3/2}$, F=4 initially increases and then decreases, starting to decline at 85°C. Simultaneously, the transmission peaks on either side of the spectrum reach their highest points. This trend persists even if the temperature is further increased to 90°C.Therefore, the optimal operating temperature is identified to be between 80°C and 85°C. After fine-tuning the operating temperature, we determined that the optimal temperature is 81.5°C, where the highest transmission peak of the spectrum is precisely aligned with the cyclic transition line $5^2S_{1/2}$, F=3→$5^2P_{3/2}$, F=4.

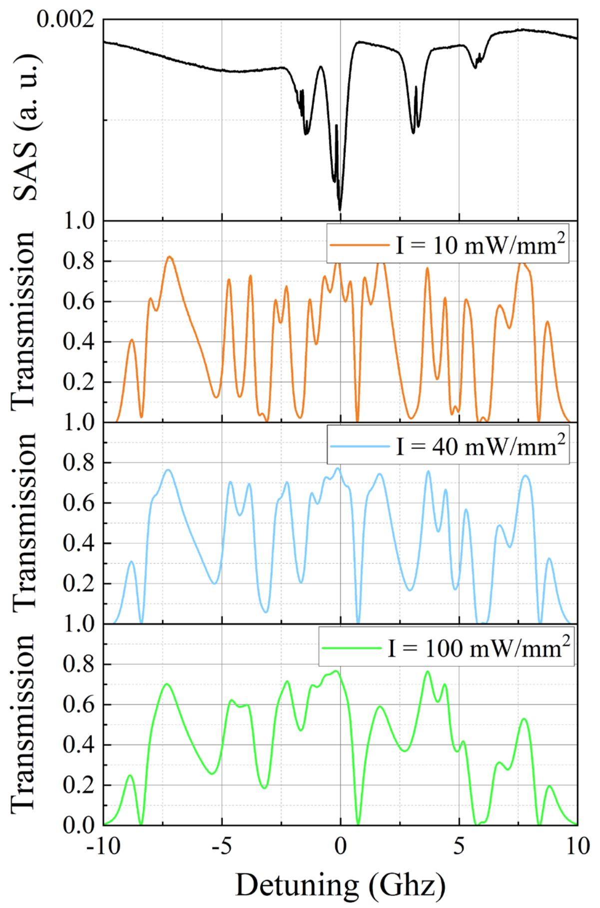

Fig. 3. Transmission spectrum of VADOF at different light intensity. The figure at top presents the saturated absorption spectrum of Rb

At 81.5°C, we studied the VADOF transmission spectrum under different light intensities. When the light intensity is 10 mW/mm², there is a transmission peak aligned with the atomic transition line, but the bandwidth is relatively narrow. In this state, constructing the laser can lead to mode hopping. However, as the light intensity increases, the bandwidth of the transmission peak gradually broadens, and the transmission peak aligned with the atomic transition line becomes the highest transmission peak. At this point, the output frequency of the Voigt laser can align with the cyclic transition line, resulting in a more stable output. Since the laser's normal operating output power ranges from 10 to 30 mW, it can be calculated that the intracavity power is approximately 4.8 times the output power. Therefore, the intracavity light intensity range is from 48 to 144 mW/mm². Therefore, when the Voigt laser operates with a magnetic field of 3700 G and a working temperature of 81.5°C, the VADOF transmission spectrum should be similar to the transmission spectrum at 100 mW/mm² shown in Fig. 3.

Under the optimal parameters, the relationship between the wavelength of our constructed Voigt laser and the laser diode current is shown in Fig. 4a. As the current increases from 80 mA to 170 mA, the output laser wavelength remains around 780.2437 nm within a 1.4 pm range, corresponding to the cyclic transition line $5^2S_{1/2}$, F=3→$5^2P_{3/2}$, F=4 of ^{85}Rb. Additionally, we use a PZT to scan the output frequency of the Voigt laser and observed the saturation absorption spectrum, as shown in HH 4b. This spectrum corresponds to all transition lines from the ground

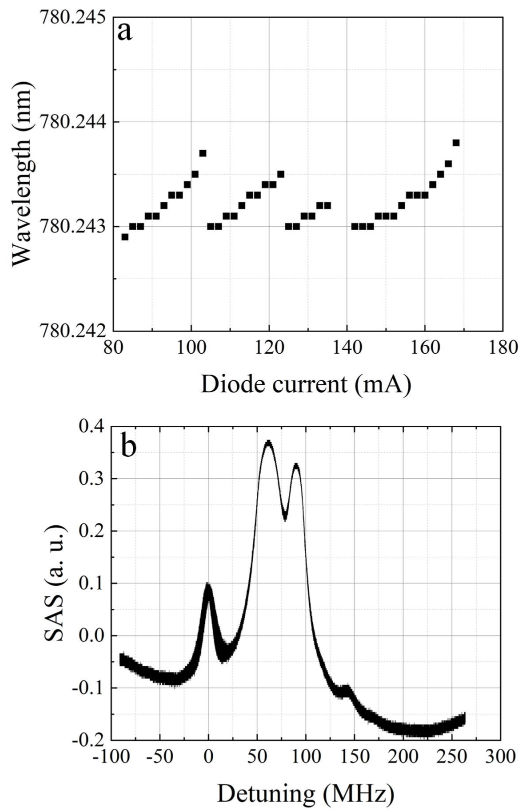

Fig. 4. (a) Wavelength of Voigt laser at different diode current. (b) saturated absorption spectrum of the Voigt laser.

state F=3 of ^{85}Rb. Regardless of the Voigt laser diode current, we consistently observe the saturation absorption spectrum in Fig. 4b, demonstrating the Voigt laser's excellent performance in automatically aligning with atomic transition lines.

IV. CONCLUSION

In summary, we explored and analyzed the key parameters affecting the VADOF transmission spectrum and selected the parameters that best meet our requirements. Specifically, we chose parameters that align the peak of the VADOF transmission spectrum with the atomic transition line and achieve a transmission of 78%. Using a VADOF with a magnetic field of 3700 G and a working temperature of 81.5°C as the frequency-selective element, we constructed a Voigt laser that directly aligns with the $5^2S_{1/2}$, F=3→$5^2P_{3/2}$, F=4 cyclic transition line of ^{85}Rb. Experimental results demonstrate that, regardless of variations in the laser parameters, the Voigt laser consistently remains near the transition line and reliably produces the required saturation absorption spectrum. This makes the Voigt laser promising for future applications, such as frequency locking using modulation transfer spectroscopy or the development of devices related to atomic transition lines. With its highly stable performance, related atomic devices based on the Voigt laser is expected to achieve plug-and-play functionality, significantly expanding the application scenarios.

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