

Potassium Faraday lasers for atomic magnetometry

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The atomic magnetometer exhibits high sensitivity in weak magnetic field detection, with diverse applications in dark matter detection, biomagnetic sensing, wireless communication, etc. However, its performance, especially in environmental robustness and sensitivity, is largely limited by laser characteristics. Here, we realized two potassium Faraday lasers operating at potassium D1 (770 nm) and D2 (767 nm) lines, serving as pump and probe lasers for a potassium atomic magnetometer. Utilizing the Faraday anomalous dispersive effect for frequency selection, the lasers achieve automatic wavelength locking within the atomic Doppler broadening, enabling robust, self-stabilizing operation without tedious adjustments. Furthermore, both lasers exhibit strong immunity to environmental disturbances, such as vibration and temperature variations. By implementing the modulation transfer spectroscopy (MTS) technique, the frequency stability of the pump laser and probe laser reaches approximately $5.1 \times 10^{-13}/\sqrt{\tau}$ and $6.2 \times 10^{-13}/\sqrt{\tau}$, respectively. Notably, the optimized frequency stability is accompanied by better power stability, showing threefold and fivefold improvements over their free-running counterparts, which reaches the 10^{-5} level at 1 s. The enhancements in laser performance directly improved the magnetometer's performance, yielding a magnetic noise floor of approximately $100 \text{ fT}/\sqrt{\text{Hz}}$ at 10 Hz under a bias field of 1000 nT. Therefore, with hands-off operation, environmental robustness and competitive sensitivity, this achievement holds promising prospects for both laboratory and field-deployable applications.

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I. INTRODUCTION

As a precision quantum-based device, the atomic magnetometer demonstrates excellent sensitivity and a wide dynamic range for weak magnetic field detection [1–4]. These advantages have facilitated its deployment in various scientific domains, including biomagnetic sensing [5–7], dark matter detection [8,9], and wireless communication [10,11]. As application scenarios extend from controlled laboratory settings to practical field deployments, there is a growing need for improved environmental

adaptability and operational robustness in the atomic magnetometer system [12], placing increasingly stringent requirements on laser performance.

In conventional atomic magnetometer systems, diode lasers, such as distributed feedback lasers [13], distributed Bragg reflector lasers [14], are typically employed. These lasers can offer compact designs and broad frequency tuning ranges. Nevertheless, they lack inherent wavelength specificity to frequency references, thereby requiring regular calibration before each start-up. In addition, during prolonged operation in harsh environment, the laser frequency may deviate away from the target value significantly due to mechanical vibrations and ambient temperature shocks. Although frequency stabilization techniques, such as dichroic atomic vapor laser lock (DAVLL) [15], saturated absorption spectroscopy (SAS) [16,17], and numerous innovative methods [18–20], can stabilize the laser frequency, they fail when the frequency drift exceeds the servo range, resulting in laser unlocking.

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Furthermore, the laser performance, including line-width, frequency and power stability, etc., can impact the magnetometer sensitivity. This is because in the atomic magnetometer system, pump and probe lasers resonantly interact with atoms to generate and detect spin polarization [21,22]. On the one hand, since the probe laser carries the magnetic resonance information, its relative intensity noise (RIN) could translate into the detection noise floor. On the other hand, fluctuations in laser frequency and power contribute to the system's technical noise [18,23]. When operating at nonoptimal frequencies, both lasers may induce light shifts that perturb the ground-state magnetic sublevels [24].

Based on the above analysis, the Faraday laser emerges as a promising source [25–29]. Its core advantage lies in the use of a Faraday anomalous dispersion optical filter (FADOF) for frequency selection, which restricts the laser wavelength to within the atomic Doppler broadening [28,29], enabling self-stabilizing operation precisely at the target wavelength. Nevertheless, realizing a viable potassium FADOF seems challenging. Unlike rubidium and cesium, potassium's narrower hyperfine splitting renders conventional operation in the weak-field Zeeman regime inadequate, as concurrent optical interactions with multiple hyperfine transitions generate a complex multi-peak spectrum, exacerbating system instability. Moreover, achieving D1 line emission is more challenging due to its lower oscillator strength, which imposes a temperature-related trade-off: low temperatures yield insufficient dispersion for stable laser oscillation, whereas high temperatures cause line-wing peaks to dominate, shifting the lasing wavelength away from atomic transitions.

To overcome these limitations, we operate the potassium FADOF in a strong magnetic field to decouple the nuclear spin from the total electronic angular momentum. It simplifies the atom interaction and purifies the transmission spectrum by suppressing spurious parasitic peaks. Crucially, the resonant line-center peak reaches the transmittance required for stable lasing prior to the line-wing peaks, ensuring stable emission at the target atomic transition.

Furthermore, we identified an intrinsic advantage of the potassium Faraday laser regarding power stability. Typically, aside from gain-medium fluctuations, laser power instability is driven by FADOF transmittance variations and frequency jitter. Once the transmittance fluctuations are suppressed via optimized temperature control, frequency jitter emerges as the dominant factor, driving frequency-to-amplitude conversion via the FADOF's transmission spectrum. To mitigate this, we employ an incident optical intensity four orders of magnitude above the saturation intensity. Under such intense optical pumping, severe power broadening merges residual near-degenerate spectral features, flattening the dominant transmission peak into a broad, flat structure.

This flattened profile minimizes the system's sensitivity to minor frequency jitter. Consequently, by employing a high signal-to-noise ratio frequency stabilization technique, the power stability can be further enhanced.

In this work, we achieved potassium Faraday lasers operating at 770 and 767 nm, respectively, serving as pump and probe lasers for an atomic magnetometer. Through the investigation of the FADOF transmission properties, both lasers adopt a similar architecture while achieving stable and automatic operation at their respective target wavelengths. Key characteristics, including wavelength, RIN, phase noise, etc., were evaluated to assess environmental adaptability and overall performance. To further improve the laser stability, modulation transfer spectroscopy (MTS) technique was implemented for frequency locking, achieving the frequency stability of $5.1 \times 10^{-13}/\sqrt{\tau}$ for the pump laser and $6.2 \times 10^{-13}/\sqrt{\tau}$ for the probe laser. Corresponding improvements in power stability were also observed, with a threefold and fivefold enhancement compared with their free-running conditions, reaching the 10^{-5} level at a 1 s integration time. These advances contribute to an improved signal-to-noise ratio (SNR) of the atomic magnetometer. Under a bias magnetic field of 1000 nT, the system achieved a magnetic noise floor of approximately $100 \text{ fT}/\sqrt{\text{Hz}}$ at 10 Hz. Benefiting from its hands-off operation, environmental robustness, and competitive sensitivity, this atomic magnetometer exhibits strong potential for deployment in complex field environments, suggesting broad applicability across a range of practical scenarios.

II. EXPERIMENTAL SCHEME

Both the 770 nm pump laser and the 767 nm probe laser are potassium Faraday lasers, sharing the same structural configuration as illustrated in Fig. 1(a). The entire laser system adopts an integrated design, which comprises a homemade laser diode serving as gain medium, a potassium atom-based FADOF for frequency selection, and an external cavity for laser oscillation. To ensure operational robustness under harsh environmental conditions, several measures are implemented.

First, to suppress the intracavity mode emission, which exhibits high sensitivity to ambient temperature fluctuations, the front facet of the laser diode is coated with an anti-reflection film with a reflectivity below 0.03%. Second, to improve the system's robustness against mechanical vibrations, the external cavity mirror and all adjustable components are glued in place. Third, the FADOF employs a compact, integrated architecture, as shown by the white component in the left panel of Fig. 1(a). Its core optical assembly consists of a pair of polarizing beam splitters (PBS) with orthogonal polarization, a 3 cm cylindrical vapor cell filled with natural potassium, and a permanent magnet. Through the Faraday

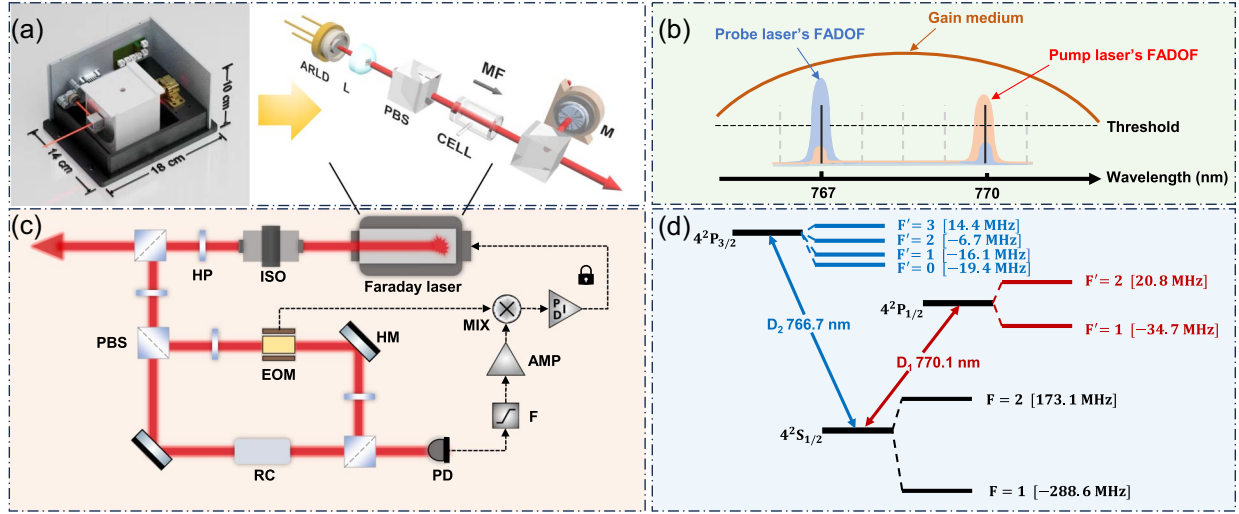


FIG. 1. (a) Structure of the potassium Faraday laser (left: physical structure; right: internal components). (b) Schematic of the frequency selection mechanism. The blue and red curves represent the FADOF transmission spectrum within the 767 nm probe laser and 770 nm pump laser, respectively. Black solid and gray dashed lines indicate the existing and suppressed cavity modes, respectively. (c) Experimental setup of the potassium Faraday laser with MTS stabilization. (d) The energy level structures of the ^{39}K at both D1 line and D2 line. F and F' denote the total angular momentum quantum numbers (electronic plus nuclear) of the ground and excited states, respectively. ARLD, anti-reflection laser diode; L, lens; PBS, polarizing beam splitter; CELL, potassium atom-based vapor cell; M, cavity mirror; MF, magnetic field; ISO, isolator; HP, half-wave plate; HM, 45° -high-reflection mirror; EOM, electro-optical modulator; RC, reference vapor cell; PD, photodetector. F, electronic filter; AMP, amplifier; MIX, mixer; PID, proportional-integral-differential locking system.

anomalous dispersive effect, the polarization of linearly polarized light with wavelength close to the atomic transitions undergoes rotation [30,31]. The rotated light is then reflected by the second PBS, enabling laser oscillation between the laser diode and the cavity mirror.

It is noteworthy that, compared with rubidium and cesium, potassium possesses distinctive energy level structures [see Fig. 1(d)], characterized by a narrow spectral separation of only 3 nm between its D1 and D2 lines, as well as small hyperfine splittings among each sub-levels [32,33]. These properties elevate the risk of mode competition, potentially leading to undesirable multi-mode emission. The challenge is further compounded by the temperature-related trade-off, making stable single-frequency operation at the desired wavelength challenging. To overcome these limitations, we applied a strong magnetic field to decouple the nuclear spin and total electronic angular momentum of the atomic ensemble, which suppresses chaotic weak-field transitions and drives the system into a linear Zeeman regime, refining the transmission spectrum to a few dominant peaks.

Specifically, to match the laser wavelength precisely with the atomic transition, the transmission spectrum of the FADOF is carefully designed to ensure a high-transmittance peak exclusively at the target wavelength, while the transmittance at other frequencies should be sufficiently low [as shown in Fig. 1(b)]. Under these conditions, the external cavity mode [indicated by the black line in Fig. 1(b)] can only be sustained within a narrow

spectral region centered around 770 nm for the pump laser and around 767 nm for the probe laser. If the cavity mode shifts away from this region, it falls below the oscillation threshold due to the sharp decline in FADOF transmittance. Conversely, any new external cavity mode aligned with the FADOF transmission peak remains sustained. Detailed procedures for designing the FADOF transmission spectrum are provided in Appendix A. In the experiment, the vapor temperatures of the pump and probe lasers are maintained at 101°C and 90°C , respectively, under a uniform magnetic field of 1000 G.

Benefiting from advanced electronic servo-feedback systems, techniques for locking the laser frequency to narrow-linewidth atomic transitions, or to high-finesse optical cavity modes, have demonstrated high effectiveness. Among them, MTS stabilization [34–36] stands out as a suitable choice for our application. Compared with SAS or DAVLL, MTS signals offer a higher SNR, enabling better frequency discrimination and stabilization. In addition, in comparison with the Pound-Drever-Hall technique [37,38], the MTS stabilization offers the advantages of lower cost, reduced environmental sensitivity, and better portability, making it well suited for practical deployment beyond laboratory settings.

The corresponding experimental setup is illustrated in Fig. 1(c). All optical components are integrated on an aluminum substrate, with the entire assembly occupying less than 3U rack units of volume. Through four-wave mixing within the reference vapor cell, the modulation

information applied by an electro-optic modulator (EOM) is transferred from one laser beam to another, which is subsequently detected and demodulated to extract the MTS signal, serving as the error signal. To minimize the influence of ambient temperature fluctuations on the quantum reference frequency, the reference vapor cell incorporates a double-layer structure: an inner chamber filled with natural potassium and an intermediate vacuum layer to reduce thermal conduction. External thermal insulation is further improved using a multilayer passive assembly made of nitrile foam and polyurethane. To enhance the sensitivity of the MTS signal for frequency discrimination, we optimized the laser power and the operating temperature of the reference vapor cell (as detailed in Appendix B). In addition, to suppress the residual amplitude modulation effect, a half-wave plate is installed before the EOM, and the EOM temperature is stabilized at 25°C [36,39].

The MTS signal is then fed into a servo-feedback system, which produces a servo signal to regulate both the laser driving current and the external cavity length. The servo-feedback system adopts an intelligent design that incorporates automatic atomic transition recognition, one-click laser locking, and autonomous relocking capability, thereby enabling continuous frequency stabilization without the need for manual intervention.

III. RESULTS

A. Wavelength self-stabilization and robustness

As mentioned earlier, in contrast to conventional diode lasers that employ gratings or interference filters for frequency selection, the characteristics of the potassium Faraday laser are governed by the FADOF. The transmission properties of the FADOF are determined exclusively by intrinsic physical parameters, such as operating temperature and applied magnetic field, rather than by vibration-sensitive quantities like angle or position, rendering its transmission spectrum highly resilient to mechanical shocks. Therefore, once the operating parameters are optimized, the laser wavelength is naturally confined around the atomic transitions. This mechanism not only endows the potassium Faraday laser with self-stabilizing capability but also facilitates robustness against environmental disturbances.

Figure 2(a) presents the laser power as a function of the diode current, with maximum power reaching 18 and 26 mW for the pump and probe lasers, respectively. Synchronous wavelength monitoring confirms that, across all diode currents above the threshold, the laser wavelength remains consistently within the Doppler broadening. In addition, we deliberately varied the diode temperature and measured the wavelength after the laser had fully restabilized, which we monitored in real time of less than 100 s, a duration primarily governed by the temperature

controller's response time and proportional-integral-differential (PID) parameters. As illustrated in Fig. 2(b), throughout the temperature range of 10–30°C, the laser maintains stable and reliable operation, with wavelength variations remaining within 1.5 pm.

We used a counter to monitor the frequency deviations of the beating signal generated by the heterodyne between two identical potassium Faraday lasers operating at 770 nm. The counter gate time is set at 0.001 s. Figure 2(c) displays the measured frequency fluctuations after removal of the linear drift. At around 90 s, a mechanical vibration disturbance was introduced by tapping the optical bench, resulting in instantaneous frequency jitter. Nevertheless, the frequency of the beating signal restabilized within approximately 5 s, consistently returning to its predisturbance value without observable offset or mode hopping.

To verify the long-term stability and environmental robustness of the laser systems, we monitored the continuous wavelength fluctuations. Taking the 770 nm pump laser as an example, the system was first placed in an uncontrolled environment devoid of active temperature regulation and optical vibration isolation. Its free-running wavelength fluctuations were monitored for over eight hours. As shown in Fig. 2(d), the long-term wavelength jitter was measured to be a mere 0.8 pm. Furthermore, to simulate the broad temperature ranges typically encountered in field applications, the laser system was placed inside an environmental test chamber with a temperature control accuracy of 0.1°C. We subjected the system to a severe step-wise temperature shock from 30 to 10°C and monitored the real-time wavelength response under this extreme thermal stress. To accurately capture the actual thermal dynamics experienced by the laser, a thermistor was mounted on the laser cavity and tracked via a 6.5-digit multimeter. The wavelength performance is presented in Fig. 2(e). It is evident that the laser operates reliably across the entire range from 10 to 30°C. More importantly, while large-scale thermal variations inevitably induce corresponding frequency shifts, unlike conventional external cavity diode lasers, which will undergo unpredictable wavelength drift away from the target value, the self-stabilizing mechanism of the potassium Faraday laser inherently constrains frequency excursions. That is, when the frequency approaches the boundary defined by the FADOF, a mode-hopping instantaneously switches the longitudinal mode and resets the frequency back within the atomic Doppler broadening.

A practical advantage of this behavior emerges during MTS frequency stabilization. Although external perturbations will cause a temporary loss of lock, the laser frequency remains located near the atomic transition. Consequently, the feedback servo can rapidly relocate the linear capture range of the MTS error signal to execute an automated relock.

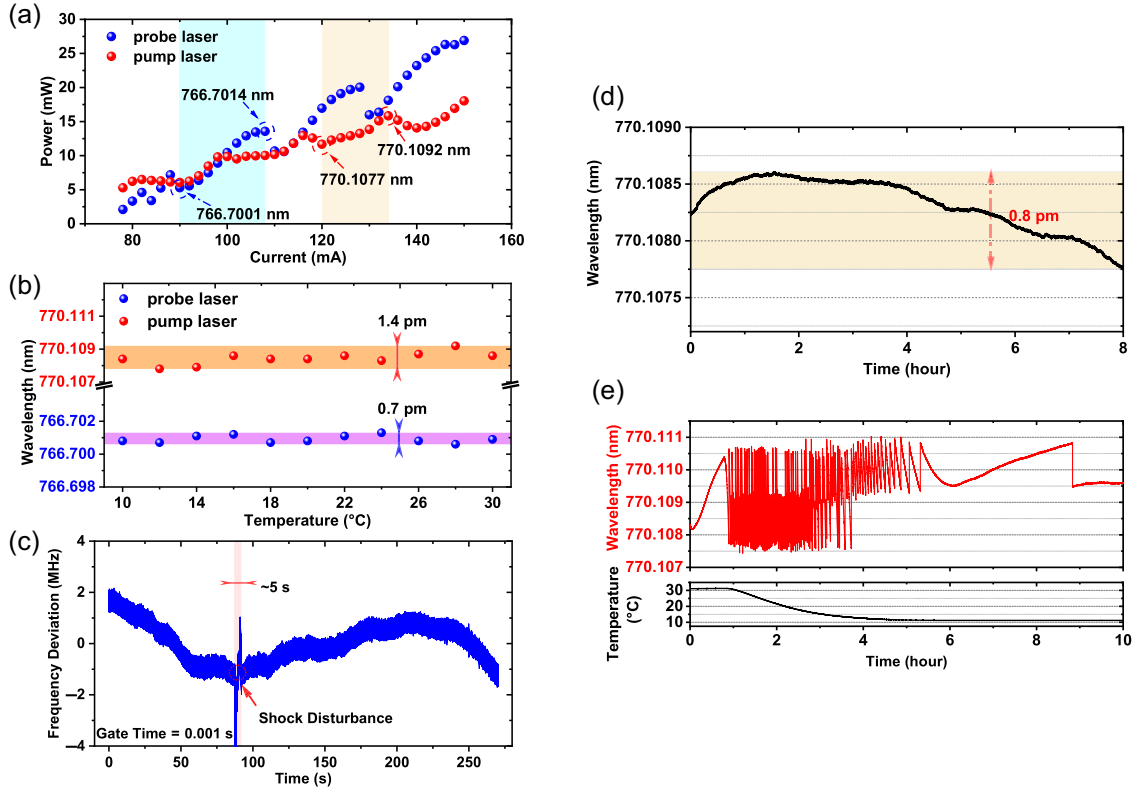


FIG. 2. Self-stabilizing capability and environmental resilience of the potassium Faraday laser. (a) Laser power versus the diode current from 80 to 150 mA. The dashed circle indicates the laser wavelength under simultaneous monitoring. (b) A typical result of the laser wavelength versus the diode temperature from 10 to 30 °C. The red and blue dots represent the pump and probe lasers, respectively. (c) A typical result of the frequency deviation of the beating signal before and after artificial vibration shock, with the counter gate time set to 0.001 s. The result is modified by removing drift. (d) Real-time wavelength fluctuations of the 770 nm pump laser monitored over a continuous 8-hour period in an unregulated environment. (e) Real-time wavelength fluctuations (red line) during an ambient temperature drop from 30 to 10 °C. The black line represents the actual laser cavity temperature monitored via a thermistor.

B. Noise level

The laser noise level is widely recognized as a critical factor influencing the SNR of the atomic magnetometer system, primarily comprising RIN and phase noise. Here, we first measured the RIN of both lasers under identical conditions, with the optical power incident on a photodetector maintained at 1.33 mW. The corresponding shot noise level is calculated to be -154.1 dBc/Hz. As shown in Fig. 3(a), the black curve represents the electronic noise floor measured without optical input, while the red and blue curves correspond to the RIN spectrum of the pump and probe lasers, respectively, with both RIN levels below -137 dBc/Hz at 10 kHz offset frequency. At high frequencies, the RIN level converges toward the shot noise limit. Figure 3(b) shows the phase noise of the beating signal generated by the optical heterodyne experiment. The integral linewidth is then determined using the $1/\pi$ integral linewidth method [40,41]:

$$\phi_{\text{rms}}^2 = \int_{\Delta\nu}^{\infty} S_{\phi}(f) df = \frac{1}{\pi} [\text{rad}^2], \quad (1)$$

where $S_{\phi}(f)$ represents the phase noise, f is the offset frequency, $\Delta\nu$ is the $1/\pi$ linewidth. By setting the upper integration limit to 1 GHz, the integral linewidth of the pump and probe lasers is 8.8 kHz and 8.5 kHz, respectively.

C. Frequency and power stability

Figures 4(a) and 4(b) show the SAS and MTS signals obtained by scanning the laser frequency, which cover all ^{39}K D1 and D2 lines, respectively. For the ^{39}K D2 lines, due to the narrow energy level spacing among the excited states, which is comparable to the natural linewidth, the MTS signal cannot resolve individual transition features [42]. It is observed that MTS signals have a high SNR with steep slopes at frequencies corresponding to atomic transitions, while maintaining a flat baseline at other frequencies. This characteristic suppresses the Doppler background, thereby enabling accurate frequency discrimination and stable laser locking. Through a custom servo-feedback system, we lock the pump

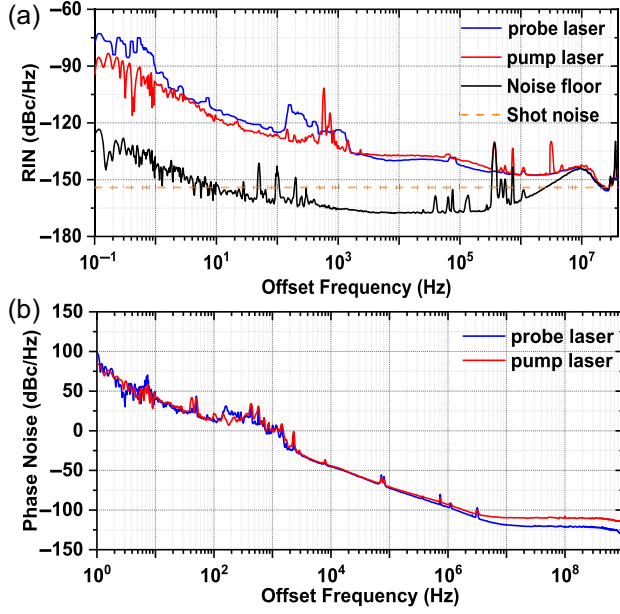


FIG. 3. (a) Relative intensity noise (RIN) of the potassium Faraday laser. The black line indicates the noise floor without incident light. The orange dots indicate the shot noise level. (b) Phase noise of the beating signal measured by two identical laser systems. The red and blue lines represent the pump and probe lasers, respectively. Both lasers operate in the free-running state without active stabilization.

laser to $^{39}\text{K } 4S_{1/2} F = (1, 2) \rightarrow 4P_{1/2} F' = 2$ and the probe laser to $^{39}\text{K } 4S_{1/2} F = 2 \rightarrow 4P_{3/2} F'$.

The frequency stability is measured through the optical heterodyne experiment between two identical systems. As presented in Fig. 5(a), a significant improvement in frequency stability is observed after MTS stabilization, with an increase of almost three orders of magnitude at the 1 s averaging time. Linear fit curves indicate that the Allan deviations of the beating signal are $7.2 \times 10^{-13}/\sqrt{\tau}$ and $8.7 \times 10^{-13}/\sqrt{\tau}$. Therefore, assuming that both systems contribute equally to the beating signal, the stability of the single laser is derived to be $5.1 \times 10^{-13}/\sqrt{\tau}$ and $6.2 \times 10^{-13}/\sqrt{\tau}$ for the pump and probe lasers, respectively.

As shown by the blue curves in Figs. 5(b) and 5(c), the power stability of the pump and probe lasers under free-running conditions approaches 1×10^{-4} at integration times below 1 s. This performance arises from the flat-top, broadband transmission spectrum of the FADOF. In addition, the implementation of MTS technique leads to a noticeable improvement in laser power stability. We attribute this primarily to the enhanced frequency stability, which further mitigates residual frequency-to-amplitude conversion within the FADOF system. As shown by the red curves in Figs. 5(b) and 5(c), the power stability of the pump and probe lasers reaches approximately 3.2×10^{-5} at 1 s and 3.8×10^{-5} at 1 s, respectively, representing

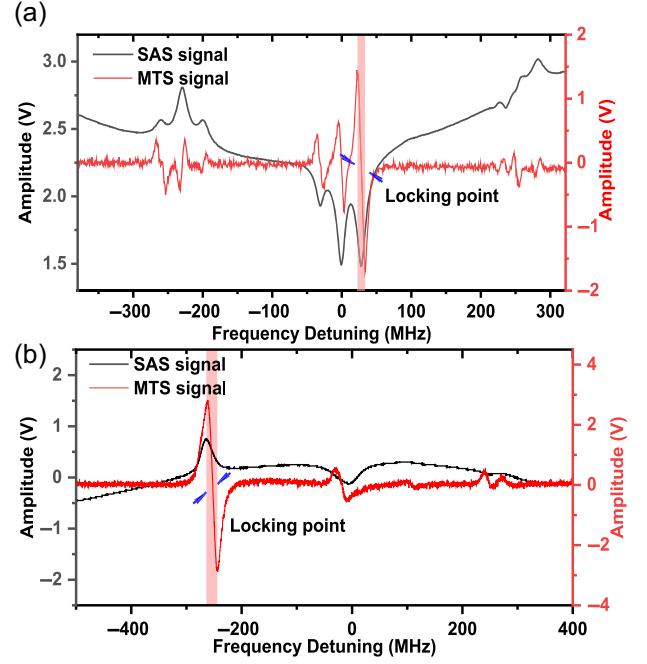


FIG. 4. (a) SAS and MTS signals at potassium D1 line. From left to right, the peaks correspond to the transitions $^{39}\text{K } 4S_{1/2} F = 2 \rightarrow 4P_{1/2} F'$, $^{39}\text{K } 4S_{1/2} F = (1, 2) \rightarrow 4P_{1/2} F'$, and $^{39}\text{K } 4S_{1/2} F = 1 \rightarrow 4P_{1/2} F'$. (b) SAS and MTS signals at potassium D2 line. From left to right, the peaks represent the transitions $^{39}\text{K } 4S_{1/2} F = 2 \rightarrow 4P_{3/2} F'$, $^{39}\text{K } 4S_{1/2} F = (1, 2) \rightarrow 4P_{3/2} F'$, and $^{39}\text{K } 4S_{1/2} F = 1 \rightarrow 4P_{3/2} F'$. The black and red lines represent the SAS and MTS signals, respectively. The blue arrows show the MTS locking point.

nearly threefold and fivefold improvements over the free-running state.

IV. APPLICATION IN AN ATOMIC MAGNETOMETER

As previously mentioned, the potassium Faraday lasers offer advantages of self-stabilizing operation and high immunity to environmental disturbances, which facilitates the hands-off operation of the atomic magnetometer. Furthermore, the competitive frequency and power stability achieved via the MTS technique can benefit magnetometer sensitivity by reducing system noise levels, as detailed in Supplemental Material [43].

Figure 6(a) shows the experimental configuration in which potassium Faraday lasers serve as pump and probe sources within an atomic magnetometer system. The laser systems and the sensor module adopt a physically separated design, where the sensor module, enclosed within a multilayer magnetic shield to attenuate ambient magnetic field gradients, receives both lasers via single-mode polarization-maintaining optical fibers. Specifically, the pump laser, amplitude-modulated by an acoustic-optic modulator (AOM), transfers angular momentum to the

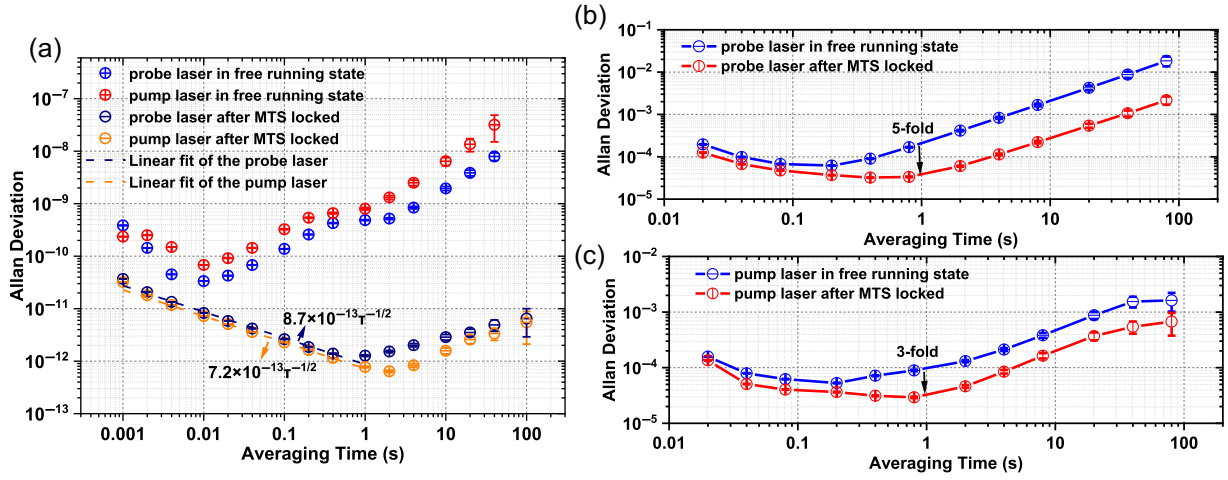


FIG. 5. (a) Frequency stability of the beating signal through optical heterodyne. The red dots and blue dots represent the pump laser and probe laser in free-running operation, respectively. The orange dots and black dots correspond to the pump laser and probe laser after MTS stabilization. Dash lines are corresponding linear fit curves. (b) Power stability of probe laser before (blue) and after (red) MTS locked. (c) Power stability of pump laser before (blue) and after (red) MTS locked.

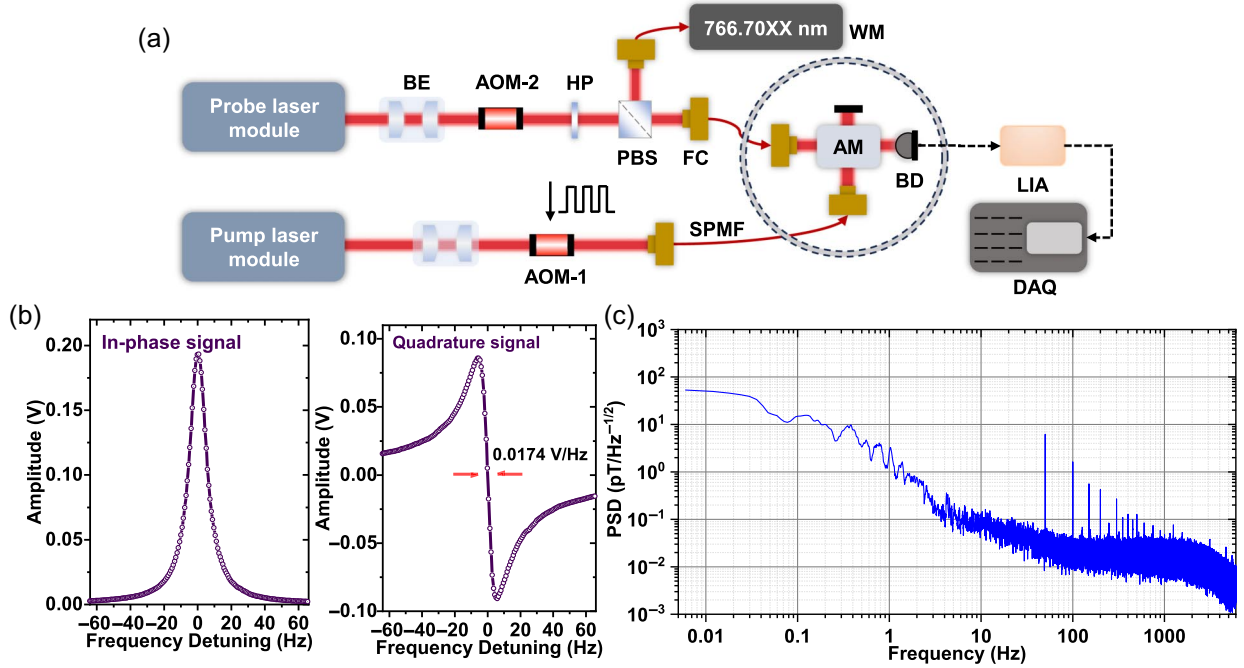


FIG. 6. (a) Experimental setup of the atomic magnetometer based on potassium Faraday lasers. BE, zoom beam expander; HP, half-wave plate; PBS, polarizing beam splitter; FC, fiber coupler; AOM, acoustic-optic modulator; AOM-1 is used for generating the amplitude modulation of the pump laser at the Larmor frequency; AOM-2 is used for tuning the probe laser's frequency; WM, wavelength meter; SPMF, single-mode polarization-maintaining fiber; AM, atomic magnetometer sensor module; BD, balanced photodetector; LIA, lock-in amplifier; DAQ, data acquisition system. The duty cycle of the driving signal for AOM-1 is 0.15%. The time constant of the lock-in amplifier is 30 μs . (b) The recorded in-phase (left) and quadrature (right) components of the magnetic resonance signal. (c) Power spectrum density (PSD) of the potassium atomic magnetometer. The bias magnetic field is kept at 1000 nT.

potassium atomic ensemble to establish macroscopic spin polarization. When the modulation frequency approaches the Larmor precession frequency of the atoms, resonant spin polarization is continuously generated and amplified.

For detection, the orthogonally propagating probe laser in linear polarization monitors the dynamical evolution of the atomic spin polarization through the Faraday effect. After passing through a paraffin coated potassium vapor cell,

the probe laser's polarization is detected by a balanced photodetector and subsequently demodulated using a lock-in amplifier. By scanning the modulation frequency of the pump laser across the Larmor precession frequency, a magnetic resonance signal is obtained, with its in-phase and quadrature components shown in Fig. 6(b).

The sensitivity of an atomic magnetometer can be estimated as [44]:

$$\delta B_{\min} = \frac{1}{\gamma} \frac{N}{(dS(\omega)/d\omega)|_{\Delta\omega=0}} = \frac{k_F}{\gamma} \frac{\Gamma}{S/N}, \quad (2)$$

where γ denotes the gyromagnetic ratio, N represents the root-mean-square noise level obtained after averaging over a given time interval, S is the maximum signal amplitude, Γ refers to the total resonance linewidth, k_F is the resonance form factor, and $\Delta\omega = \omega - \omega_0$ with ω_0 being the magnetic resonance frequency. Therefore, enhancing the magnetometer's sensitivity primarily involves optimizing the magnetic resonance signal, aiming to maximize the ratio of its amplitude to the linewidth S/Γ .

Based on the above analysis, we implemented several optimizations. First, since the probe laser is resonant with the atomic transition, it induces an undesirable optical pumping effect [18]. To mitigate this effect, we employed a set of frequency-tunable AOMs to tune the laser frequency. Furthermore, to improve the interaction efficiency with the atomic ensemble and minimize optical power loss, we utilized a zoom beam expander to tailor the beam profile. This adjustment enhanced both the diffraction efficiency of the AOMs and the fiber coupling efficiency.

Experimentally, we set the duty cycle of the driving signal for modulating the pump laser at 0.15% and the time constant of the lock-in amplifier at 30 μ s. Under an applied bias magnetic field of 1000 nT, an optimized magnetic resonance signal was observed with 0.19 V in amplitude and 11.03 Hz in full width at half maximum, as shown in Fig. 6(b). Subsequently, we set the pump laser's modulation frequency to the Larmor frequency and maintained it constant. The recorded quadrature signal, measured by the lock-in amplifier, was converted into temporal magnetic field fluctuations. The power spectral density (PSD) was then derived through a Fourier transform. As shown in Fig. 6(c), the magnetic noise floor is about 100 fT/ $\sqrt{\text{Hz}}$ at 10 Hz.

We believe the performance of the potassium Faraday laser can be further improved to achieve lower system noise in the atomic magnetometer. For instance, as shown in Figs. 5(b) and 5(c), laser power stability degrades at longer integration times. This degradation primarily stems from the limited temperature control precision of both the ARLD and the FADOF vapor cell, causing fluctuations in spontaneous emission power and FADOF transmittance. Furthermore, AOMs and polarization-maintaining

single-mode fibers are sensitive to ambient temperature variations, which can also lead to fluctuations in the laser power delivered to the magnetometer sensor.

Future work will address long-term power stability through several approaches. Beyond active stabilization methods, such as servo-feedback loops utilizing AOMs or liquid crystal retarders, we will improve the temperature control precision on key components by implementing a fully digital system with high-resolution analog-to-digital converters and digital PID algorithms. Additionally, to further strengthen the system's robustness and portability, we will work on miniaturizing the laser system by adopting a more compact design and eliminating all adjustable components, with the ultimate goal of achieving chip-scale integration.

V. CONCLUSION

In conclusion, we demonstrate the implementation of potassium Faraday lasers as pump and probe lasers in an atomic magnetometer system. The intrinsic atomic frequency selection mechanism enables the laser wavelength to automatically align with the ^{39}K relevant transitions with strong robustness against environmental disturbance. By adopting the MTS technique, the frequency stability of both lasers is enhanced, achieving $5.1 \times 10^{-13}/\sqrt{\tau}$ and $6.2 \times 10^{-13}/\sqrt{\tau}$, respectively. Furthermore, the power stability is also improved, with enhancements of 3 and 5 times, respectively. The utilization of potassium Faraday lasers improves the performance of the atomic magnetometer, primarily in two aspects. On the one hand, the robust, self-stabilizing operation of the lasers ensures the adaptability of the atomic magnetometer in complex environment. On the other hand, the competitive linewidth, stability enhances the SNR of the magnetometer system. Under optimized operational parameters, the potassium magnetometer achieves a magnetic noise floor of approximately 100 fT/ $\sqrt{\text{Hz}}$ at 10 Hz under a bias magnetic field of 1000 nT. This achievement demonstrates the system's potential for deployment in various environments, with applications in biomagnetic field detection, geophysical surveying, and wireless communication.

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The authors declare no competing interests.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX A: TRANSMISSION CHARACTERISTICS OF THE POTASSIUM ATOM-BASED FADOF

Fundamentally, the lineshape and absolute transmittance of the FADOF spectrum depend on the atomic absorption and dispersion properties, which are affected by the vapor temperature, magnetic field, and incident laser intensity. To achieve optimal operating conditions, we systematically analyzed these parameters.

The primary objective is to automatically match the laser wavelength to the atomic transition while simultaneously minimizing the risk of multimode oscillation. This necessitates a smooth FADOF transmission profile with minimal spurious peaks in the off-resonant wings. To achieve this, we elected to operate in a strong magnetic field to decouple the nuclear spin (I) and total electronic angular momentum (J). This ensures that transitions are governed by $\Delta m_J = \pm 1$ and $\Delta m_I = 0$, eliminating hyperfine spectral interference. Furthermore, to suppress mode competition from adjacent longitudinal modes, the FADOF transmission bandwidth should match the 1 GHz free spectral range of the planned 12.5 cm laser cavity. Based on these considerations, an optimal magnetic field strength of 1000 G was selected through theoretical calculations [29].

To further engineer a smooth, flat-top transmission profile while suppressing off-resonant line-wing transmittance, the laser intensity incident upon the FADOF was set to 20 mW/mm², exceeding the saturation intensity by approximately four orders of magnitude. Given that the typical output power of the potassium Faraday laser is on the order of 10 mW [see Fig. 2(a)], we achieved this intensity by collimating the beam size to approximately 1 mm² (at the 1/e² level). Under such intense optical pumping, severe power broadening merges any residual near-degenerate spectral features, reshaping the dominant transmission peak into a broad, flat structure. Concurrently, the intense optical field depletes the ground-state atomic population, inducing dispersion saturation. Consequently, the Faraday rotation angle diminishes substantially at off-resonance frequencies, resulting in a marked attenuation of the line-wing transmittance.

In addition to magnetic field and laser intensity, the vapor temperature also requires precise adjustment, as it alters the optical depth and the Faraday rotation angle. To determine the optimal operating temperature,

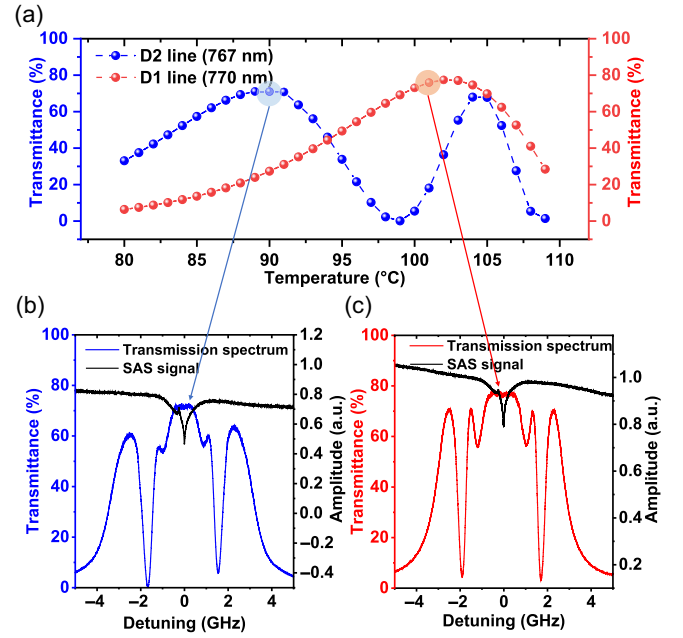


FIG. 7. (a) Transmittance of the potassium FADOF at line-center peak versus vapor temperature from 80 to 110 °C. The red and blue curves represent the D1 and D2 lines, respectively. (b) Transmission spectrum of the potassium FADOF at the D2 line, operating at a cell temperature of 90 °C and a magnetic field of 1000 G. The blue and black lines represent the transmission spectrum and the SAS signal, respectively. (c) Transmission spectrum of the potassium FADOF at the D1 line, operating at a cell temperature of 101 °C and a magnetic field of 1000 G. The red and black lines represent the transmission spectrum and the SAS signal, respectively.

we measured the FADOF transmission spectrum under different temperatures. As shown in Fig. 7(a), the transmittance at the frequency corresponding to the D1 line (i.e., the line-center peak at D1 line) reaches its maximum across the range from 101 to 104 °C. However, as the temperature approaches 104 °C, the transmittance at the D2 line also increases significantly, thereby introducing the risk of dual-mode emission. Therefore, the operating temperature for the pump laser was set at 101 °C. Similarly, to maximize the transmittance at the D2 line while suppressing interference from the D1 line, the vapor temperature for the probe laser is set to 90 °C.

Figures 7(b) and 7(c) display the resulting FADOF transmission spectrum at D2 and D1 lines, respectively. It can be observed that the maximum transmission peak completely encompasses the target atomic transition while maintaining an absolute transmittance exceeding 70%. Furthermore, transmittance at far detunings (>4 GHz) is suppressed to nearly zero. This excellent out-of-band rejection ratio ensures laser oscillation with the desired wavelength.

APPENDIX B: OPTIMIZATION OF THE MTS SIGNAL FOR FREQUENCY DISCRIMINATION

Laser frequency stability is typically expressed as [45]:

$$\sigma_y(\tau) = K \frac{\Delta\nu}{\nu_0 \cdot \text{SNR} \cdot \sqrt{\tau}} = K \frac{1}{\nu_0} \frac{N}{D} \frac{1}{\sqrt{\tau}}, \quad (\text{B1})$$

where ν_0 is the central laser frequency, N represents the overall noise in the laser system, $D = S/\Delta\nu$ defines the slope of the frequency discriminator, τ is the integration time, and K is a proportionality constant. Therefore, optimizing locking performance primarily depends on maximizing the discriminator slope D and minimizing the overall noise N .

To evaluate the slope D , we calculated the ratio of the target MTS signal's peak-to-peak amplitude to its corresponding frequency interval. To quantify the system's

noise floor N , we sampled the baseline noise at a frequency far detuned from the atomic resonance and obtained its noise power spectral density (S_n) through a fast Fourier transform. Because the resulting spectrum confirmed that the baseline noise exhibits white-noise characteristics at frequencies above 1 Hz, S_n can reflect the broadband noise floor N . Consequently, we adopted the equivalent frequency noise, defined by the ratio S_n/D , as our primary evaluation criterion to optimize the laser locking system [35].

Guided by this criterion, we systematically investigated the optimal operating points for three key parameters, including the power of the pump and probe beams within the MTS setup, and the temperature of the reference vapor cell. The results are presented in Fig. 8. Specifically, regarding the probe beam power, as illustrated in Figs. 8(a) and 8(d), it is evident that an increase in probe beam power leads to a larger frequency discriminator slope D .

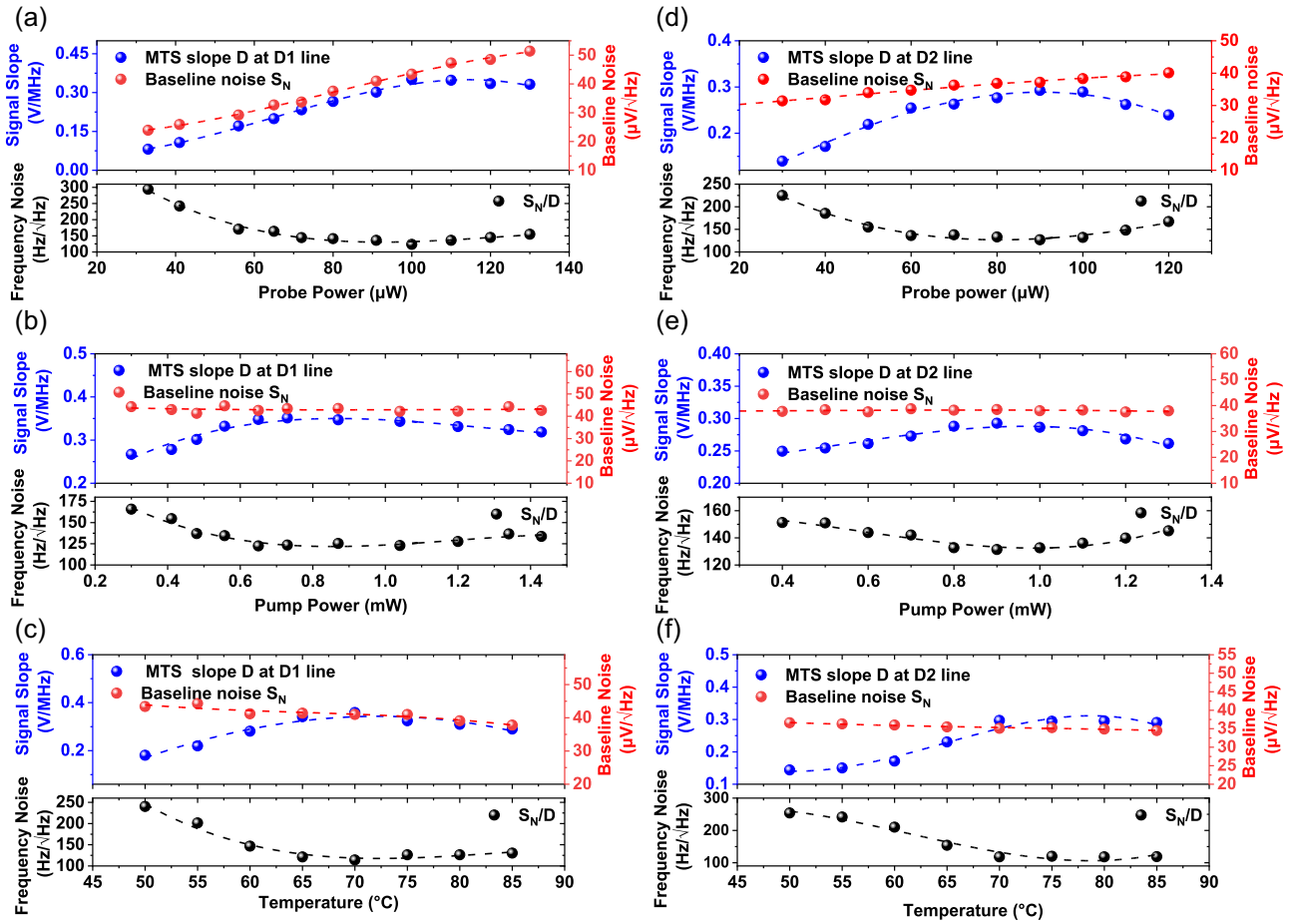


FIG. 8. Optimization of the MTS signals, including the frequency discriminator slope D (blue), baseline noise power spectral density S_n (red), and equivalent frequency noise (S_n/D) (black), as a function of the MTS probe beam power, pump beam power, and reference vapor cell temperature. (a)–(c) Optimization for the D1 line by varying: (a) probe power (pump power fixed at 0.8 mW); (b) pump power (probe power fixed at 0.1 mW); and (c) cell temperature (pump and probe power fixed at 0.8 and 0.1 mW, respectively). (d)–(f) Optimization for the D2 line by varying: (d) probe power (pump power fixed at 0.9 mW); (e) pump power (probe power fixed at 0.09 mW); and (f) cell temperature (pump and probe power fixed at 0.9 and 0.09 mW, respectively). All optical powers are measured before entering the reference vapor cell.

However, the baseline noise also increases as the noise floor is governed by the laser's RIN, which scales proportionally with the probe power. Furthermore, when the probe beam power exceeds a certain threshold, it induces optical pumping effects, thereby limiting the modulation transfer efficiency and causing the slope D to approach saturation. As for the pump beam depicted in Figs. 8(b) and 8(e), the slope D initially increases with rising pump power within the low-power regime. However, it eventually begins to decline due to the effects of deep saturation broadening. Finally, as shown in Figs. 8(c) and 8(f), the temperature of the vapor cell dictates the atomic number density. Initially, raising the temperature increases the population of atoms participating in the interaction, resulting in a rapid increase in the slope D . Nevertheless, once the temperature exceeds 70°C, the excessively high atomic density exacerbates collision broadening effects, thereby reducing the slope of the MTS signal.

The optimal operating parameters were determined by minimizing S_n/D . For the pump laser, the optimal parameters were found to be an MTS pump beam power of 0.8 mW, an MTS probe beam power of 0.1 mW, and a cell temperature of 70°C. In contrast, for the probe laser, the optimal operating parameters were an MTS pump beam power of 0.9 mW, an MTS probe beam power of 0.09 mW, and a vapor cell temperature of 70°C.

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