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ABSTRACT
In this work, an efficient method for frequency stabilization of a highly off-resonant laser in a spin-exchange relaxation-free atomic inertial sensor is proposed. This was accomplished via the use of an optical resonator that transferred the stability of an atomic energy level to the laser frequency. The pump laser frequency was stabilized via saturation absorption spectroscopy and was used as a reference to lock the large-detuned probe laser with a double transmission Fabry–Pérot (FP) cavity. The frequency stability and bandwidth of the entire transfer cavity frequency locking system were investigated, and the results were used to elucidate the effect of cavity length on stability. The frequency stability of the system approached $1.66 \times 10^{-11}$ when the FP cavity length was 30 mm. This method can be applied to a variety of ultrasensitive atomic physics experiments, such as for precision spectroscopy and laser cooling.

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I. INTRODUCTION
Laser frequency stabilization is a primary requirement for high-precision optical measurements in a wide range of applications, such as precision spectroscopy,1 optical communications,2 laser gyroscopes,3 and atomic gyroscopes.4 Furthermore, several ultrasensitive measurement devices require extremely high stability over large detunings, such as spin-exchange relaxation-free (SERF) atomic magnetometers that are used for both magnetic field and inertia measurement. Atomic magnetometers are based on the polarization of alkali atoms by a pump laser in the presence of an external magnetic field, which is then measured by the optical rotation of a probe laser.5 The frequency of free-running lasers may drift by several GHz per day because of temperature and current fluctuations. A slow drift is mainly caused by the influence of the ambient environment on the laser cavity and results in laser frequency instability, which is detrimental for precision experiments. Active frequency stabilization is generally used to lock a laser with respect to an atomic transition or a stable reference frequency.7–12 For several applications, the highly stable Fabry–Pérot (FP) cavity is chosen as the reference.13–15 Frequency modulation spectroscopy,16 polarization spectroscopy,17 dichromatic atomic vapor laser locking,18 and Signac interference19 are widely used laser stabilization techniques. The Faraday effect20 and the Doppler-free dichroic lock technique21 are used for laser frequency stabilization at large detuning from the atomic reference line. However, velocity-selective optical pumping22 and saturated absorption spectroscopy (SAS) with Zeeman shifts23 require a high-quality magnetic field generation and stabilization device or an ultra-high vacuum. Furthermore, resonant interferometry24,25 provides a small detuning range of about several hundred MHz for laser stabilization. The utilization of a diffraction grating in the Littrow configuration and simultaneous resonant optical feedback from a confocal FP cavity26 have been reported to provide a large detuning range of 1–10 GHz; however, this requires a complicated method of tuning the detuning by adjusting the atomic density and the thickness of the gas chamber. Moreover, the error
signal decreased with decreasing frequency detuning, and it could not be generated when the detuning frequency was less than ±1 GHz. Additionally, the detuning could not be precisely controlled in this study.

FP cavities and similar optical resonator cavities exhibit excellent frequency discrimination performance and are widely used for the frequency stabilization and tuning of lasers.\textsuperscript{26–29} To this end, we proposed a large-detuned laser locking technique based on the transfer of the frequency stability from an FP cavity for an SERF atomic inertial sensor. The sensor requires two frequency stabilized laser sources: the pump laser is used to excite and dress the atomic spin states, and the SAS technique is used to stabilize its frequency; the probe laser is used to detect the atomic spin precession frequency. The probe laser is highly detuned with respect to the resonant frequency of the working medium, and therefore, it cannot be stabilized by SAS. Here, the transfer cavity lock method is used, and the extremely high stability of the FP cavity is transferred to both the pump and probe lasers. The bandwidth and stability of the transfer cavity frequency locking system were analyzed, and the effect of cavity length on the stability was investigated. The frequency stability of the system approached $1.66 \times 10^{-11}$. This method is potentially useful for a wide range of applications that require stabilization of lasers at a large-detuned atomic-reference frequency, such as the generation of correlated photons in an atomic vapor.

The work carried out in this report is novel and will be of benefit for research into laser frequency locking. While researchers have used an ultra-stable FP cavity to lock the laser frequency, our work focuses on the influence of the cavity length on this locking system and the short-term stability/response of the locking system. To the best of our knowledge, this has not been previously reported and will be of help for the selection of cavity parameters for different research purposes.

**II. METHOD**

Active frequency stabilization is usually implemented for stabilizing the frequency of semiconductor diode lasers. The transfer cavity lock method is widely used for the frequency stabilization of semiconductor lasers. The length of an FP cavity is sensitive to the external environment, and the transmission peaks can drift by several hundred MHz to GHz. Therefore, the FP cavity needs to be locked as well. For this, the transmission peak of the pump laser of the SERF inertial measurement device is used to lock the length of the FP cavity. The pump laser is locked using the SAS technique. After the cavity length of the FP cavity is locked, the transfer cavity lock method is used; then, the probe laser is locked to a cavity mode of the FP cavity. In this paper, both the pump laser and the beat reference laser are external cavity semiconductor lasers, and the feedback signals used for frequency stabilization are fed back to the corresponding piezoelectric ceramic transformer (PZT). The FP cavity controls the cavity length through the PZT; therefore, the feedback signal used to control the cavity length is fed back to the PZT. The probe laser is a distributed Bragg reflector (DBR) semiconductor laser, and the feedback signal used to stabilize the laser frequency is fed back to the current source as shown in Fig. 1(a). In the following part, the frequency drift of the laser source and FP cavity mode were analyzed in the transfer cavity frequency locking system, and the stability of system output frequency was measured with the beat frequency method. Furthermore, the frequency drift of the lasers and the FP cavity mode during the free operation of the whole frequency stabilization system as well as the bandwidth of the system were analyzed. The stability of the system output frequency was measured with the beat frequency method. Finally, the influence of the FP cavity length on the stability of the system was analyzed.

In our SERF atomic inertial sensor, the pump laser (780-nm external cavity laser) was locked to a crossover resonance of $^{87}\text{Rb}$
(2 → 3,1) via the SAS. This laser was then used to lock the probe laser [770-nm distributed Bragg reflector (DBR) laser] at the central transmission peak of the FP cavity. This implies that both the pump and probe lasers were stabilized simultaneously. The experimental system for this beat note measurement is shown in Fig. 1.

A temperature controller was not used in our frequency stabilization system to facilitate the miniaturization and integrability of the sensor and to reduce its complexity. The experimental system was put in a dark box built with a black acrylic plate, and some insulation and sound insulation measures were taken to avoid the influence of temperature and air fluctuation on the experiment. However, they still had an impact on the system; therefore, the free-running frequency drift of each part of the system was measured using the SAS and FP cavity modes, as described in Subsections II A–II F.

A. Measurement of the frequency drift in the free-running pump laser

Traditionally, the laser frequency drift is measured by scanning the transfer cavity. In this work, a simple method was used for the measurement of laser frequency drift based on the SAS transmission spectrum. A 780-nm external cavity diode laser (Uniquanta, ECL801) was used as the pump laser. The frequency interval of 78.4735 MHz between two crossover resonances (2 → 3, 1 and 2 → 3, 2) of the 87Rb D1 line was selected as the frequency scale. The frequency drift of the pump laser causes the SAS to drift, as shown in Fig. 2. Therefore, the frequency drift during the free operation of the laser was realized by measuring the relative time shift of these resonances, according to the following equation:

$$df = (dx/\Delta x) \times \Delta f,$$

where $\Delta f$ is the frequency difference between the two crossover resonances, $\Delta x$ is the corresponding time interval between them, $dx$ is the shift in position of the crossover resonance 2 → 3,1 from its initial time, and $df$ is the frequency drift of the free-running laser. The experimental results are shown in Fig. 4(a).

Figure 4(a) shows that the frequency drift is positively correlated with the external temperature. Therefore, the external temperature sensitivity coefficient (ETSC) is defined as the ratio of the maximum drift to the maximum variation of the external temperature. The frequency drift changed dramatically (the ETSC = −748 MHz/K) when the temperature varied from 25.38 °C to 25.75 °C. However, it changed much more slowly (ETSC = 461 MHz/K) when the temperature varied from 25.28 °C to 25.38 °C. The average ETSC of the free-running pump laser over the whole measurement range was 580 MHz/K. Apart from external temperature variations, these drifts are also caused by external airflow disturbances. To realize high sensitivity for the inertial measurement device, the laser frequency stability should be in the MHz order or better. The SAS technique can stabilize the frequency to several hundred kHz, which is suitable for frequency stabilization of the pump laser.

B. Measurement of the shift in the frequency of FP modes

The frequency stabilized pump laser beam was used to lock the FP cavity length. Two transmission peaks were obtained by scanning the FP cavity. The frequency interval between these peaks was equal to the free spectral range (FSR) of the FP cavity, which was selected as the frequency scale. A commercial scanning FP interferometer (Thorlabs, SA200-5B) with a cavity length of 50 mm (FSR = 1.5 GHz) was used for this study.

When the incident laser frequency of the FP cavity was stable, a variation in the cavity length caused a shift in the frequency of the FP modes, and thereby, the transmission peaks were shifted as well, as shown in Fig. 3. This frequency shift of the cavity modes can be obtained by measuring the relative time drift of the transmission peaks as follows:

$$df = (dx/\Delta x) \times FSR,$$

where $\Delta x$ is the time interval between two adjacent transmission peaks, $dx$ is the relative position drift of one transmission peak, and $df$ is the frequency drift of the FP mode, and FSR is the free spectral range (FSR) of the FP cavity.

The experimental results are shown in Fig. 4(b). The cavity mode drifted by ~372 MHz at 25.264 °C. The frequency drift changed dramatically (~7.319 GHz/K) when the temperature varied from 25.26 °C to 25.307 °C; however, it changed much more slowly (~1.699 GHz/K) when the temperature varied from 25.307 °C to 25.339 °C. The average ETSC of the FP cavity mode was 6.211 GHz/K. These drifts were mainly caused by external temperature variations and low-frequency vibrations. Therefore, the length of the FP cavity should be locked with a stable pump laser for frequency sensitive measurements.

![FIG. 2. Saturated absorption spectroscopy (SAS) corresponding to pump laser frequency drift.](image-url)
C. Measurement of the frequency drift in the free-running probe laser

The locked FP interferometer, which has the same order of stability as that of the pump laser, was then used to measure the frequency drift of our homemade free-running probe laser. The frequency stabilized pump laser beam was used to lock the FP cavity length. First, one transmission peak spectrum was obtained by scanning the FP cavity. Then, the cavity length was locked to the top of the transmission peak. Next, the transmission peak spectral signal was sent to the phase-locked amplifier, which amplified it to obtain the primary differential signal of the spectral signal. Finally, this differential signal was taken as an error signal and fed back to the PZT in the FP cavity through the PID controller to achieve cavity length locking. When the cavity length was locked, the probe laser was scanned to obtain two transmission peaks (corresponding with two adjacent FP cavity modes). The frequency difference between the two cavity modes was equal to the FSR, which was independent of the incident laser frequency, as given by the following equation:

\[
\text{FSR} = \frac{c}{2nL},
\]

where \(n\) is the refractive index of the medium in the FP cavity, \(L\) is the cavity length, and \(c\) is the speed of light in vacuum. The frequency drift measurement method of the probe laser is similar to that in Sec. II A, except that when the length of the FP cavity was locked, the frequency drift of the cavity mode was caused by the frequency drift of the probe laser. The frequency drift of the free-running probe laser was, therefore, obtained from the drift of the cavity mode. The experimental results are shown in Fig. 2(c). It is evident in this figure that the frequency drift of the laser was almost linearly proportional to the ambient temperature. These drifts were mainly caused by external temperature variations \(^{30-32}\) and airflow disturbances \(^{33}\). The ETSC of probe laser was 690 MHz/°C. However, the ETSC is larger (\(\sim 761\) MHz/°C) when the temperature varies from 25.25 °C to 25.26 °C. The ETSC required for the SERF inertial measurement device is \(\sim 10\) MHz/°C to 25 MHz/°C. Therefore, the frequency of the probe laser needs to be stabilized to reduce the ETSC so that the frequency is not affected by the external temperature as far as possible.

D. Measurement of frequency stability of the probe laser

1. Step 1: Stabilization of the reference laser

The reference laser was locked to the potassium D1 line (\(\sim 770.1083\) nm) using the SAS technique. Because the SAS signal of the potassium is weak, a 10-cm-long potassium cell was selected for a better signal-to-noise ratio.
2. **Step 2: Selection of probe laser frequency**

Beat note locking was used to measure the frequency stability of the probe laser. To obtain beat notes, the frequency difference between the reference laser and the probe laser was controlled within 1.5 GHz. The temperature of the probe laser was set to a fixed value (33.8 °C), and a series of cavity modes were obtained by scanning the current of the probe laser. Finally, the probe laser was locked to the cavity mode with a wavelength of ~770.10771 nm, which corresponded to 150 mA of laser current.

3. **Step 3: Beat notes**

The frequency difference between the probe and reference lasers was 300 ± 30 MHz. We used an avalanche photodiode (APD; Thorlabs APD210) and a spectrum analyzer (Keysight Technologies, N9322C) to measure the beat signal. Figure 3 shows that the frequency of the measured beat signal is ~312 MHz, which is consistent with the frequency difference between the two lasers.

**E. Measurement of closed-loop bandwidth**

An active modulation was applied to the system for measuring its closed-loop bandwidth. When the entire system was stabilized, 10 mV modulation signals with different frequencies were applied to the pump laser. The output spectrum, shown in Fig. 5, exhibits a poor signal-to-noise ratio, which may be attributed to the following two factors: light feedback from the strong reflection of the FP cavity and the vibration in the cavity due to external noise. The useful signal from the spectrum was extracted with a lock-in amplifier and amplified; it was then used to stabilize the frequency of the pump laser. The output spectrum, shown in Fig. 5, the green, blue, and red curves represent the applied modulation signal, the output spectrum, and the error signal, respectively. The modulation signal and error signal were amplified 10 fold and 40 fold, respectively, for clarity. A significant phase delay between the error signal and the modulation signal was evident in this figure, which may be attributed to the delay in the frequency stabilization process. The amplitude of the error signal may be considered as the response of the system to the external modulation. The closed-loop bandwidth of the system was obtained from the modulation frequency with an amplitude reduction of ~3 dB. The bandwidth was obtained as 480 Hz, which is sufficiently high for SERF magnetometers. For other experimental systems, this bandwidth may not be enough. The bandwidth of the system may be limited by the response frequency of the FP cavity. When the length of the FP cavity was locked on the pump light, its external response frequency was limited or affected. In addition, the cavity length adjusted by the PZT and FP cavity has a certain inflexibility and cannot respond to a modulation frequency that is too high. Therefore, a faster FP cavity length adjustment structure or method may be required to improve the system bandwidth.

**F. Effect of cavity length on stability of laser frequency**

Because the FP cavity plays a key role in the entire frequency stabilization system, its performance and length govern the frequency stability of the probe laser. Therefore, the effect of different cavity lengths on the frequency stability was compared. The reference cavity was a 30-mm FP cavity (UniQuanta, FP-30-780). The intracavity refractive index R (R = 98.75%) and the refractive index of the medium in the FP cavity n (n = 1.0) for the two FP cavities were the same, and the material for the two cavities was also the same. Therefore, because the two cavities have similar specifications, a fair comparison of the two measurements can be carried out. The lengths of the two cavities were the main factor influencing the frequency stability of the laser. The effects of the FP cavity length were then analyzed for the following two aspects.

1. **Effect of cavity length on the anti-vibration ability of the FP cavity**

The FP cavity was placed in a V-shaped mount that transferred its vibrations to the cavity. For low-frequency vibrations, the elastic deformation of the cavity can be analyzed by assuming that both the cavity and the mount move simultaneously with a constant acceleration, and the corresponding force is equivalent to the gravitational force in the direction along the cavity length. If coupled deformations in the other directions because of the Poisson effect are ignored, the variation of the cavity length can be expressed by

\[
\Delta L/L = -\rho a L / (2E),
\]

where L is the length of the cavity, \(\rho\) is the density of the cavity material, \(a\) is the component of acceleration in the direction of cavity length, and E is Young’s modulus of the cavity material. From Eq. (4), it can be seen that the variation of the ratio is proportional to the cavity length. The variation of the cavity length is proportional to the cavity’s sensitivity to external vibration and the frequency deviation.24

![FIG. 5. Output spectrum corresponding to the external modulation signal.](image-url)
2. Effect of F-P cavity length on the vibration resistance of the servo system

Equation (5) shows the expression for the width of the transmission peak. It shows that a short cavity exhibits a wider transmission peak than a long cavity when the reflectivity of the two FP cavity mirrors was the same (the intracavity refractive index $R = 98.75\%$). Here, the probe laser is locked to the transmission peak; therefore, as the width of the transmission peak increases, the slope of the profile near the peak decreases, which makes the servo system less sensitive to external vibrations,

$$\delta\lambda = \frac{\lambda^2 (1-R)}{2\pi n L \sqrt{R}}, \tag{5}$$

where $\delta\lambda$ is the transmission peak width, $\lambda$ is the incident light wavelength, $R$ is the intracavity refractive index, $n$ is the refractive index of the medium in the FP cavity, and $L$ is the FP cavity length.

III. RESULTS

The frequency stability of the probe laser was obtained by beating with a reference laser, as described in Sec. II. The beat note signal over a period of 6 h is shown in Fig. 6(a). It can be observed that the maximum fluctuation of the stabilized probe laser frequency was 6 MHz and the full width at half maximum of the probe beam was $\sim 1.9$ MHz [Fig. 6(b)]. During the experiment, the ambient temperature fluctuated by $0.5^\circ$C, so the ETSC corresponding to the probe laser after frequency stabilization was 12 MHz/$^\circ$C. This meets the requirements for a SERF inertial measurement device for a probe laser ETSC ($10$–$25$ MHz/$^\circ$C).

The frequency fluctuation of the reference laser was about $200$ kHz, which is $30$ times less than that of the beat signal. The Allan deviation of the beat note data over 6 h with different cavity lengths was determined and is shown in Fig. 7, which confirms the frequency stability of the probe laser.

It was observed that when the cavity length was 50 mm, the short-term frequency stability of the probe laser was $1.512 \times 10^{-9}$ (integration time of 1 s). The stability reached $1.402 \times 10^{-10}$ for an integration time of 250 s. In contrast, when the cavity length was 30 mm, the short-term frequency stability was $7.058 \times 10^{-11}$, which is $21$ times higher than for the case of the long cavity. The stability reached $1.663 \times 10^{-11}$ with an integration time of 64 s, which was $8$ times higher. Therefore, both the short-term stability and long-term stability of the short cavities were better than those of the long cavities.

In summary, the shorter cavity lengths made the FP cavity and servo control system less sensitive to external vibration. When the cavity length decreased by $40\%$, the frequency stability of the system increased by approximately one order of magnitude.

IV. CONCLUSION

In this work, a simple and reliable method for stabilizing the laser frequencies over large detuning was proposed. The ETSC of each part of the control system was evaluated by measuring the frequency drift based on the SAS and FP cavity modes. It was observed that the FP cavity exhibited the highest sensitivity to the external temperature, and its ETSC ($6.211$ GHz/$^\circ$C) was an order of magnitude larger than that of the laser. The long-term and short-term stability and the bandwidth of the transfer cavity lock system were comprehensively analyzed and quantified, and the results confirmed the feasibility of the frequency stability transfer method. After using the proposed frequency-stabilized method, a probe laser frequency fluctuation of less than $6$ MHz was realized, which caused the drift of the SERF inertial measurement device to be less than $5 \times 10^{-5}$ $^\circ$C/h. This satisfied the requirements for the SERF inertial measurement device for the probe laser. The full width at half maximum of the probe beam was $\sim 1.9$ MHz. The short-term frequency stability was
7.058 \times 10^{-11}$, and the long-term stability was $1.663 \times 10^{-11}$ with an integration time of 64 s and an FP cavity length of 30 mm. The simultaneous frequency stabilization of the pump and probe lasers was demonstrated with the SERF inertial measurement sensor.

The effect of cavity length on the stability of the system was analyzed, and it was observed that a shorter cavity length resulted in lower sensitivity of the FP cavity and servo control system to external vibrations. Furthermore, the cavity length and FSR were observed to be inversely and linearly proportional to the range of laser frequency detuning.

The stability of the system could be further improved by controlling the temperature of the FP cavity and the external environment at the same time. It was observed that low-frequency vibrations significantly influenced the FP cavity and servo control system to external vibrations. The intense optical feedback caused by the FP cavity also affected the stability of the laser, which could be circumvented by using better techniques for seismic isolation and improving the optical path structure. We believe that the proposed method is a versatile one that can be applied to a wide range of experiments in atomic physics for the stabilization of lasers at large detunings from the atomic reference.

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