Digital-locking optically pumped cesium magnetometer

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***Abstract*—Lamp-based optically pumped Cesium magnetometer is one kind of commercial quantum magnetometers. In whatever military or civil magnetic field measurement, the practical optically pump magnetometer possesses a very important application value as well as prospect. This paper presents a portable lamp-pumped and digital-locking cesium atomic magnetometer, including the probe for detecting Zeeman transition signal and the digital servo system for locking the Zeeman transition frequency based on NI PCI-4461. The probe is lamp-based and as compact as 17 cm × 6 cm × 6 cm in size. The design of the servo system is to use frequency switching (at two frequencies) to create two corresponding voltages from the probe. When the voltages are equal, the center of the two frequencies appears to be the Zeeman transition frequency. The measurement of the magnetic field is experimentally realized with the noise level of 22 pT. The magnetometer is portable and highly compact with good sensitivity and has the potential of practical usage in the future.**

Keywords—magnetometer; sensitivity; digital servo system

I. INTRODUCTION

The precision measurement of the magnetic field is necessary for the important information hidden in the extremely weak magnetic fluctuations. Alkali atomic magnetometer is attracting more and more attentions these years, due to its potential of better sensitivity and practicality. Recent work focuses on four topics: (1) the improvement of sensitivity for magnetometer in Mx- or Mz- configuration [1]; (2) the application of magnetometer arrays for practical use, like magnetic gradient measurement [2]; (3) the development of low resource, miniature magnetometer based on the techniques of MEMS fabrication [3]; (4) the exploration of different magnetometer methods for better performance [4]-[7]. Lamp-based optically pumped Cesium magnetometer (CsOPM) is one kind of commercial quantum magnetometers. In whatever military or civil magnetic field measurement, the practical optically pump magnetometer possesses a very important application value as well as prospect.

This paper presents a portable lamp-pumped and digital-locking cesium atomic magnetometer, including the probe for detecting Zeeman transition signal and the digital servo system for locking the Zeeman transition frequency based on NI PCI-4461. The probe is lamp-based and as compact as 17 cm × 6 cm × 6 cm in size. The design of the servo system is to use frequency switching (at two frequencies) to create two corresponding voltages from the probe. When the voltages are equal, the center of the two frequencies appears to be the Zeeman transition frequency. The measurement of the magnetic field is experimentally realized with the noise level of 22 pT. The magnetometer is portable and highly compact with good sensitivity and has the potential of practical usage in the future.

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II. SYSTEM MODEL

A. The probe of optically pumped magnetometer

The model of the magnetometer probe is given as follows. As shown in Fig. 1, Cs light source emits circularly polarized pump beam which propagates along z axis. External magnetic field B_0 is parallel to z axis. RF magnetic field lies along x axis and passes through Cs vapor cell. Photodiode detects the intensity of D_1 that passes through the cell.

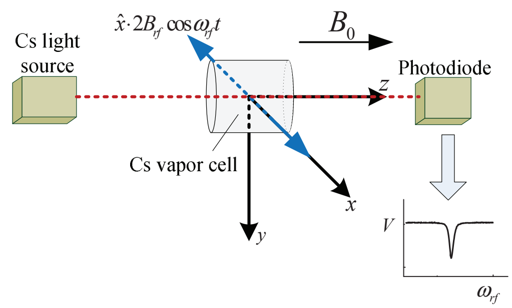

Fig. 1: Model of the probe for detecting Zeeman transition signal.

When the RF is sweeping through the Zeeman transition frequency(Larmor frequency), the transition signal in the form of absorption peak will be detected by the photodiode. The RF frequency at the absorption peak corresponds to the Zeeman transition frequency f_L. By using the relationship of $\gamma B_0 = f_L$, where γ is magnetogyric ratio, B_0 is obtained.

B. Frequency switching method for digital-locking system

The digital servo system for locking the Zeeman transition frequency is based on the so-called frequency switching method. As shown in Fig. 2, RF frequency switches between $f_C - f_\Delta$ and $f_C + f_\Delta$. Two corresponding voltages (V_- and V_+) are detected from the probe. When the voltages are equal, i.e. $V_{err} = V_- - V_+$ is zero, f_C (the center of the two frequencies) appears to be the Zeeman transition frequency f_L.

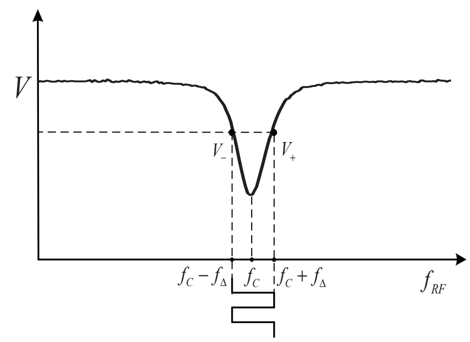

Fig. 2: Digital-locking method based on frequency switching between $f_C - f_\Delta$ and $f_C + f_\Delta$.

Specifically, if f_C deviates form f_L, V_{err} has a non-zero value. Within the range of the Zeeman transition spectrum, when f_C is on the left side of f_L, $V_{err} > 0$; when f_C is on the right side of f_L, $V_{err} < 0$. Thus, V_{err} can serve as the error signal which is then fed back to the control mechanism to keep f_C locked to f_L.

Here, it is necessary to discuss the influence of the frequency switching width (FSW) on the error signal (ES). Fig. 3 shows the ES curves under different FSW. In general, better locking effect results from greater slope of the ES curve at the Zeeman transition frequency. Thus, the curve with the FSW of 18 corresponds to the best ES among the three. In this paper, the spectral line width (LW) is defined as the frequency interval at half the signal peak. Empirically, it is appropriate to take the LW as the FSW.

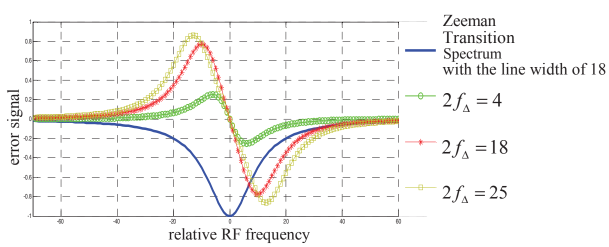

Fig. 3: Error signal (ES) curves under different frequency switching width (FSW).

III. Magnetic Measurement System

A. Description of the exprimental apparatus

Fig. 4 shows the experimental magnetic measurement system. Within the probe, D_1 from the Cs discharge lamp is circularly polarized. The normal power consumption and optical power of the lamp are 2 W and 2 mW respectively. The collimated beam is 14 mm in diameter. Photodiode detects the intensity of D_1 line that has passed through the cylindrical cell (25 mm in diameter and 25 mm long) and produces photocurrent which is converted into voltage. In order to reduce the influence of outer magnetic field, the cell is surrounded by magnetic shields. The controllable static magnetic field is generated by inner coil. The whole probing system is put into a light-proof and temperature control box in order to maintain a temperature of 40 ℃ and avoid optical interference. The servo system provides and controls RF field via RF-coils. The probing system is 17 cm × 6 cm × 6 cm in size. Currently, under laboratory conditions, the probe reaches the sensitivity of 39.2pT/Hz$^{1/2}$ [8].

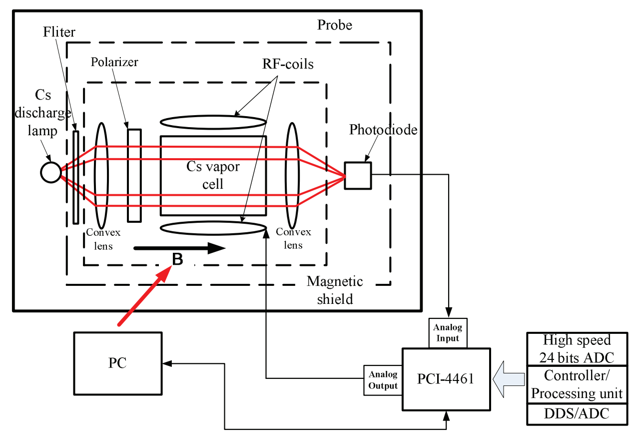

Fig. 4: Schematic diagram of the probe for detecting Zeeman transition signal and the digital servo system for locking the Zeeman transition frequency.

Besides the magnetic probe, the servo system for locking the Zeeman transition frequency is essential to the device. NI PCI-4461 is the core components, which contains high-speed 24 bits analog-to-digital converter (ADC), data processing and control unit, direct digital synthesizer (DDS), 24 bits digital-to-analog converter (DAC). The control unit is programmable and compatible with LABVIEW. NI PCI-4461 possesses some advantages. (1) The device's analog output can provide programmable RF field directly, which means software can be used directly to set and adjust f_C, FSW, RF amplitude, etc. Accordingly, since RF frequency is determined and set before issued to the RF-coil, the frequency measurement device for the ultimate f_L is unnecessary. (2) The input resolution is 24 bits with sampling rate of 204.8 kilo-Samples/s, which contributes greatly to obtain a sufficient number of high-accuracy voltage data from the photodiode. Thus, software filter can be used effectively to increase the signal-to-noise ratio. (3) The device's ability to handle large numbers of 24 bits data makes the servo process faster and more accurate. Therefore, NI PCI-4461 is qualified to apply the frequency switching method to the digital servo system.

B. Description of the digital-locking process

Based on the Zeeman transition spectrum [8], some appropriate parameters can be selected: 0.05 Vpp for RF amplitude; 300 Hz for f_Δ. After fast scanning, the center frequency f_C may locate within the range of the Zeeman transition spectrum. Then, the digital-locking process begins and goes through the following steps.

First, NI PCI-4461 issues the RF field at $f_C - f_\Delta$ and detects the voltage from the photodiode. At the sampling rate of 204.8 kilo-Samples/s, 150,000 voltage samples are obtained rapidly with 24 bit accuracy. After data processing, the voltage V_-, which reflects the intensity of D_1 that has passed through the Cs cell at the RF frequency of $f_C - f_\Delta$ will be obtained. Second, the RF field is switched to $f_C + f_\Delta$ and the device gets V_+ in the same way. Third, calculate and process the error signal $V_{err} = V_- - V_+$, which is used to adjust f_C. Then, the device repeats the three steps and eventually V_{err} appears to be very close to zero (fluctuating within the range of 10^{-5} V). At this moment, f_C is locked to f_L.

IV. Measurement results and discussion

Fig. 5 shows the 500 seconds long recording of a constant magnetic field with the NI PCI-4461 based digital-locking Cs magnetometer operated with the frequency switching method. The frequencies are converted to magnetic field units. The upgrade rate of the field value appears to be 0.625 Samples/s. Here, we treat the peak-to-peak fluctuation of the measured magnetic field as the noise level. Thus, at the rate of 0.625 Samples/s, the noise level of the NI PCI-4461 based digital-locking Cs magnetometer is about 22 pT.

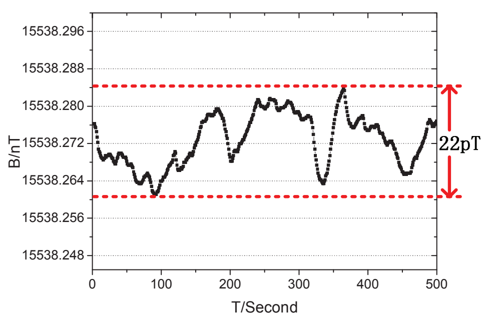

Fig. 5: 500 seconds long recording of a constant magnetic field with the NI PCI-4461 based digital-locking Cs magnetometer operated with the frequency switching method.

In consideration of the fact that the real magnetic environment changes all the time, how the device performs under this condition reflects the quality of the measurement. We change the static magnetic field several times and record the performance of the magnetometer. Each time, we finish the operation within 1 second. Fig. 6 shows the response of the magnetometer to the changing field. The recording illustrates that the system possesses the ability to keep up with the changes. For example, at the 50th second, the field changes from 15425 nT to 15550 nT. The system responds immediately and the record is stabilized to the new value after 30 seconds.

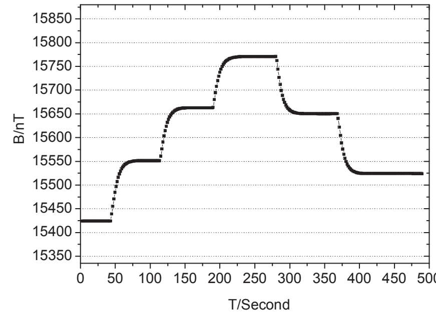

Fig.6: Recordings of the magnetometer's response to the change of the magnetic field.

V. Conclusion

This paper presents a portable lamp-pumped and digital-locking cesium atomic magnetometer, including the probe and the digital servo system based on NI PCI-4461. The probe is lamp-based and compact in size. The frequency switching method is realized and performs well to lock the Zeeman transition frequency. According to the recording, the noise level of the magnetometer is about 22 pT at the rate of 0.625 Samples /s. The magnetometer is portable and highly compact with good performance and has the potential of practical usage in the future.

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