Design of the self-oscillating loop of the optically pumped cesium magnetometer

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Abstract. The self-oscillating loop is an important part of the optically pumped cesium magnetometer, and its working characteristics directly determine the accurate measurement of external magnetic field. The design of the self-oscillating loop has been discussed in this paper, including a signal conditioning circuit, a phase shifter and a frequency meter. It can be used to precisely improve the accuracy of resonance signal in a wide range of frequencies from 50 kHz to 350 kHz. The relative error of our system is less than $0.5 \times 10^{-6}$ and it has a good prospect in the optically pumped cesium magnetometer.

1. Introduction
In recent years, the sensitive detection of weak magnetic field plays an increasingly important role in many fields, such as industrial engineering [1], biomedicine [2], military science [3] and other fields. Based on the optically detected magnetic resonance of cesium atoms process, the optically pumped cesium magnetometer (OPCM) [4] is a widely used magnetic field detection instrument with the advantages of high sensitivity, high accuracy and high response speed. As an important part of the OPCM, the self-oscillating loop converts the measurement of magnetic field strength to the measurement of signal frequency. Therefore, how to design a self-oscillating loop to meet the working condition of high accuracy is the key to improve the accuracy of OPCM.

The self-oscillating loop is mainly composed of a signal conditioning circuit, a phase shifter and a frequency meter. Many scholars have made detailed research on part of the self-oscillating loop. Chen et al. [5] adopted a five-stage stagger tuned amplification to amplify the resonance signal, but the design of frequency meter is not given. Marković et al. [6] proposed a microwave phase shifter based on memristor. The feasibility of the design is analysed theoretically, but there is no practical application. Tang et al. [7] proposed a 90° phase shifting network. This design scheme has a wide operating frequency range, but its accuracy is not high enough for the OPCM. As to the frequency measurement, Buajarern et al. [8] used optical frequency comb technique to take an absolute frequency measurement, but this method is only simulated and cannot be applied in the OPCM due to its huge test platform. The frequency measurement accuracy of other software algorithms, such as fast Fourier Transform [9], short-time Fourier transform [10] and all-phase fast Fourier transform (apFFT) method [11][12], is limited by...
the number of points and the time of FFT transform, which cannot meet the continuous and high-speed frequency measurement requirements of OPCM.

In recent years, the development of high-accuracy OPCM has attracted the attention of many scholars. Although there is much research on individual parts of the self-oscillating loop, a few on design of the whole circuit system. In this paper, we designed a self-oscillating loop, which can meet high accuracy requirement of the OPCM. The contributions of this work include the following points:

1) The self-oscillating loop is designed, including a low-noise signal conditioning circuit, a wideband phase shifter and a high accuracy frequency meter.

2) An indoor test and an outdoor test are carried out to prove the validity and high accuracy of our designed system in the frequency range of 50 kHz~350 kHz.

2. The principle of the optically pumped cesium magnetometer

OPCM is an optical nuclear magnetic resonance instrument, the core of which is to guarantee the Zeeman transition of cesium atoms under the external magnetic field. The typical structure is shown in figure 1. It is mainly composed of a magnetic sensor and the electronic components, among which the magnetic sensor including a cesium light, the optical lenses and a cesium vapor cell, the electronic components including a photodetector, a signal conditioning circuit, a phase shifter and a frequency meter. The magnetic sensor is used to generate a continuously stable resonance signal. The photodetector converts the optical signal into a detectable electrical signal, and continuously outputs the resonance signal through a self-oscillating loop. At this time, the exact value of the external magnetic field can be obtained by measuring its frequency, and their relation is:

\[ B = \frac{2\pi}{\gamma} f \]  

where \( f \) is the resonance frequency, and \( \gamma \) is the gyromagnetic ratio constant of cesium atoms. According to the gyromagnetic ratio constant of the \(^{133}\text{Cs}\), the corresponding frequency range of the magnetic field is from 30 kHz to 350 kHz.

![Figure 1. The structure of the optically pumped cesium magnetometer](image)

3. Design of the self-oscillating loop

3.1. Signal conditioning module

The resonance signal output by the photodetector is a weak current signal. Since the current signal is not easy to get its frequency information, a signal conditioning circuit is designed to convert the weak current signal into a voltage signal and amplify.

The signal conditioning module includes an I-V conversion circuit and a multi-stage amplification, as shown in figure 2. Then the frequency measurement of the current signal is replaced by the frequency measurement of the voltage signal. The voltage signal converted by the I-V conversion can be expressed as:

\[ U_1 = I_s \times R_i \]  

where \( U_1 \) is the output voltage signal and \( I_s \) is the input weak current signal.
Due to the wide frequency range of the weak resonance signal and the limited bandwidth of the amplifier, we designed a multi-stage amplifier circuit to amplify the voltage signal. The separation component JFET is selected to build the preamplifier and two integrated amplifiers with low noise are selected to build a two-stage amplifier. After the multi-stage amplifier circuit, the peak-to-peak of the signal can meet the requirement of accurate frequency measurement.

3.2. Phase shifter

When the OPCM works, the zero phase shift of the whole self-oscillating loop must be needed to achieve accurate magnetic measurement. A phase difference of 1° can result in 1 Hz change in the resonance frequency, which will affect the measurement of the external magnetic field. Due to the characteristics of the magnetic sensor itself, the phase of optical signal detected by the photodetector produces 90° ahead. Therefore, it is necessary to design a phase shifter with a lag of 90°.

As shown in figure 3, the phase shifter has been designed on the basis of the first-order all-pass filter. It’s transfer function is:

$$A_{\mu f}(s) = \frac{1 - RsC}{1 + RsC}$$  \hspace{1cm} (3)

The amplitude response is

$$|A_{\mu f}(j\omega)| = 1$$  \hspace{1cm} (4)

The phase response is:

$$\phi(\omega) = \arctan\left(\frac{2\omega RC}{1 - \omega^2 R^3 C^2}\right)$$  \hspace{1cm} (5)

When $\omega = 1/RC$, $\phi(\omega) = 90°$, that is, the phase of the output signal lags behind the input signal by 90°. In order to ensure that the resonance signal can accurately shift 90° at different frequencies, we used a trans conductance amplifier to build the first-order all-pass filter and a digital potentiometer to replace the resistance $R$, as shown in figure 4. When the capacitance $C$ is stable and the frequency of resonance signal changes, the control voltage $U_c$ of trans conductance amplifier is output by the digital potentiometer to make the signal accurately shifted 90°.
3.3. Frequency meter
There are many methods for frequency measurement. In order to meet the high sampling rate of OPCM and high frequency of resonance signal, we adopted the multi-cycle and equal precision method (ME), as shown in figure 5. The counting error of measured signal and the trigger error are eliminated effectively and the frequency measurement accuracy can be greatly improved.

The frequency measurement system of the ME method is built on the field-programmable gate array (FPGA) and STM32 microprogrammed control unit (MCU). As shown in figure 5, the fixed measurement gate is generated by STM32, the actual measurement gate is generated by synchronizing the measured signal and the fixed gate signal. In the actual gate, the measured signal and the standard signal are counted and a multi-gate counting signal is triggered by the rising edge of each measured signal. Assuming that in one measured cycle, \( N \) and \( n \) are the counting value of measured signal and \( k_i \) is the counting value of standard signal in the \( i \)-th multi-gate. Thus the frequency of measured signal in a single multi-gate is:

\[
f_{xi} = \frac{N + n}{K + k_i} f_s (6)
\]

In the whole measurement cycle, \( N-n+1 \) multi-gates are opened, so the average frequency of the measured signal is:

\[
f_s = \frac{N + n}{N-n+1} f_s \sum_{i=1}^{N-n+1} \frac{1}{K + k_i} (7)
\]

4. Experimental results and analysis
In order to validate the characteristic of the self-oscillating loop, we conducted an indoor accuracy test and an outdoor test.

4.1. Indoor accuracy test
In the indoor test, a current source is used to simulate the resonance signal and the signal is input into our designed system and the standard frequency meter Stanford SR620 respectively. The measurable frequency range of Stanford SR620 is 1 mHz ~ 1.3 GHz and its resolution is up to 25 ps RMS. In our proposed system, the magnetic field sampling rate is 10 Hz, that is, the frequency measurement cycle is 0.1 s, and the frequency range of input signal is 70 kHz ~ 350 kHz. The comparison results between these two methods are shown in Table 1.
Table 1. Comparison results between our designed system and Stanford SR620

| Measured signal/Hz | Our designed system | Stanford SR620 |
|-------------------|-----------------------|----------------|
|                   | Test result/Hz | Absolute error/Hz | Relative error/10^{-6} | Test result/Hz | Absolute error/Hz | Relative error/10^{-6} |
| 70000             | 69999.97175  | 0.02825  | 0.4036 | 69999.9748  | 0.0252  | 0.36 |
| 100000            | 99999.95938  | 0.04062  | 0.4062 | 99999.9623  | 0.0377  | 0.377 |
| 200000            | 199999.91825  | 0.08175  | 0.40875 | 199999.9241  | 0.0759  | 0.3795 |
| 300000            | 299999.87625  | 0.12375  | 0.4125 | 299999.8838  | 0.1162  | 0.3873 |
| 350000            | 349999.85375  | 0.14625  | 0.4179 | 349999.8642  | 0.1358  | 0.388 |

Under the influence of the current source accuracy and clock deviation of FPGA, it can be seen from Table 1 that the accuracy of our system is slightly less than that of the standard frequency meter, but the relative error of this system is less than 0.5×10^{-6}.

4.2. Outdoor test

We developed a prototype used our designed self-oscillating loop and carried out an outdoor experiment with the commercial overhauser magnetometer GSM-19 and optically pumped cesium magnetometer CS-3, as shown in figure 6.

![Figure 6 Outdoor comparison test](image)

We can see that these three curves do not completely coincide, but the variation trend of the measured geomagnetic field is basically the same, mainly because of the magnetic field gradient generated by different sensor positions. In addition, the buildings, vehicles, cables and so on also produce magnetic field gradient, but they will not affect the comparison of the three sensors. The consistency of the three curves proves that our designed system can work properly and the accuracy is consistent with that of commercial magnetometers.

5. Conclusion

In order to meet the high accuracy requirement of the OPCM, the self-oscillating loop has been designed completely in this paper, including a low noise signal conditioning circuit, an automatic wide band phase shifter and a high accuracy frequency meter. It is proved by experimental results that the accuracy of our system is less than 0.5×10^{-6} from 30 kHz to 350 kHz and works stably. It meets the requirements of the self-oscillating loop of the optically pumped cesium magnetometer. The design is simple in structure and stable in performance, and provides a scheme that involves optically pumped cesium magnetometers for the further research.

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References

[1] Yin, H., Yang, S. S., Zheng, K. H., Wen, X., Zhuang, J. H., & Wang, J. (2017). Development and application of the detecting instrument for weak magnetic field. Vacuum & Cryogenics, 23(5), 304-10.

[2] Haobin, D., & Changda, Z. (2010). A further review of the quantum magnetometers. Chinese Journal of Engineering Geophysics, 4, 013-027.

[3] Dalichaouch, Y., Czipott, P. V., & Perry, A. R. (2001, September). Magnetic sensors for battlefield applications. In Unattended Ground Sensor Technologies and Applications III (Vol. 4393, pp. 129-134). International Society for Optics and Photonics.

[4] Budker, D., & Romalis, M. (2007). Optical magnetometry. Nature physics, 3(4), 227-234.

[5] Chen, Y. T., Cheng, L., & Peng, J. J. (2014). Design on cesium optical pumping weak magnetic detection system. Journal of Wuhan University of Technology, 36(5), 600-604.

[6] Marković, I. L., Potrebić, M. M., & Tošić, D. V. (2018). Main-line memristor mounted type loaded-line phase shifter realization. Microelectronic Engineering, 185, 48-54.

[7] Tang, X., & Mouthaan, K. (2009). 180° and 90° Phase Shifting Networks With an Octave Bandwidth and Small Phase Errors. IEEE microwave and wireless components letters, 19(8), 506-508.

[8] Buajarern, J., Phuaknoi, P., Runusawud, M., & Tonmeanwai, A. (2013, May). Absolute frequency measurement by using optical frequency comb technique. In 2013 10th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (pp. 1-4). IEEE.

[9] Shen, T. A., Li, H. N., Zhang, Q. X., & Li, M. (2017). A novel adaptive frequency estimation algorithm based on interpolation FFT and improved adaptive notch filter. Measurement Science Review, 17(1), 48-52.

[10] Liu, H., Dong, H., Ge, J., Bai, B., Yuan, Z., & Zhao, Z. (2016). Research on a secondary tuning algorithm based on SVD & STFT for FID signal. Measurement Science and Technology, 27(10), 105006.

[11] Dong, C., & Ren, L. (2012, May). The design of all-phase FFT cymometer based on DSP. In 2012 International Conference on Systems and Informatics (ICSAI2012) (pp. 303-305). IEEE.

[12] Wang, M., & Zhang, X. (2015, December). Method for frequency measurement with ApFFT based on FPGA. In 2015 IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC) (pp. 1177-1180). IEEE.