

Article

Noise Analysis in Pre-Amplifier Circuits Associated to Highly Sensitive Optically-Pumped Magnetometers for Geomagnetic Applications

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Featured Application: This paper analyzes the noise characteristics of photoelectric detection circuit in frequency domain for a cesium optically pumped magnetometer. It can guide the low-noise circuit design. The influences of magnetometer due to the radio frequency (RF) power, the incident light power and the cell temperature are also investigated and improved. The optimization process is also applicable for the other types of optically pumped magnetometers.

Abstract: This paper analyzes the noise sources in photoelectric detection circuits with several low-noise operational amplifiers cores. The fabricated circuits are low-noise pre-amplifiers that are used for optically pumped magnetometers. In the proposed circuits, the noise levels of equivalent output voltage are calculated, and the results are in accordance with measurements. With a cooperation of several operational amplifiers, we select LT1028 from linear technologies as the core for our detection circuit, which has an output signal-to-noise ratio of more than 2×10^5 up to the frequency of 100 kHz. By analyzing the individual noise sources in the detection circuit, the dominant noise source is confirmed as the photocurrent shot noise below 200 kHz. Beyond this frequency, the voltage noise source in the operational amplifier dominates. Besides, the lamp power, the radio frequency (RF) power, the temperature variations, and their influences on the sensitivity are studied and optimized. Finally, an optically pumped magnetometer with cesium head is established, showing an intrinsic sensitivity of 85 fT/ $\sqrt{\text{Hz}}$. This sensitivity is realized under a geomagnetic magnetic field strength of 53 μT .

Keywords: noise analysis; low-noise detection circuit; optically pumped magnetometer; optimization

1. Introduction

The optically pumped magnetometer (OPM) is a total field measurement instrument that is able to detect an extremely weak magnetic field of fT level in uncooled conditions. The OPM's working principle is based on the responses of the Larmor frequency (LF) to an external magnetic field. The LF occurs due to the atomic precession of a gas in an isolated cavity that is filled with the sensing and buffer gas; usually, the type and fraction of the contents is artificially determined to maximize the sensitivity. Compared to the SQUID (Superconducting Quantum Interference Device) magnetometers, the OPMs are able to operate under room temperature, to provide a high resolution including a bandwidth from DC (direct current) to several hundred/thousand Hz [1–3]. Thus, the OPMs are widely used in

geophysical explorations, aerospace developments, information receiving, bio-magnetism researches, etc., [4–11].

There has been much research on the limit of detection (LOD) of OPMs in low environmental magnetic field conditions [12,13]. Groeger et al. developed a laser pumped cesium magnetometer with an equivalent magnetic noise level (EMN) of 15 fT/ $\sqrt{\text{Hz}}$ under an external field of 2 μT [14,15]. Scholtes et al. realized a miniaturized OPM in weak magnetic field with a high LOD of 42 fT/ $\sqrt{\text{Hz}}$ [16–18]. Chen et al. demonstrated a spin-exchange relaxation free (SERF) magnetometer with an EMN of 13 fT/ $\sqrt{\text{Hz}}$, which worked only in near zero field condition [19].

The noise performance of typical commercial optically pumped magnetometers used in the geomagnetic field are about several hundred fT/ $\sqrt{\text{Hz}}$. For example, the Cs-OPM “CS-3” that developed by Scintrex Company has an EMN less than 600 fT/ $\sqrt{\text{Hz}}$ [20]. The “G-824A” Cs-OPM developed by Geometrics Company can realize an EMN of 350 fT/ $\sqrt{\text{Hz}}$ [21]. The “GSMP-35” potassium-OPM from the GEM Company has an EMN of 200 fT/ $\sqrt{\text{Hz}}$ [22]. QuSpin’s total-field magnetometer is a sensor in small size and with low power consumption; however, its sensitivity is only a little bit lower than 1 pT/ $\sqrt{\text{Hz}}$ [23]. These commercial magnetometers are widely accepted by the market, but there is little information about their optimizations in design, especially the noise improvements in the associated detection circuits. Mateos et al. investigated the low frequency noise of the OPMs [24]. However, their studies included neither the condition in high environmental magnetic fields, nor the optimization of the parameters in OPMs. Although, in some investigations the parameter optimizations were involved [25–28], only the shot noise contribution induced by the incident light was considered, excluding the noise sources from the pre-amplifier.

In this paper, the noise source of the pre-amplifier circuit of the Cs-OPM is analyzed. By means of the signal characteristics in the photoelectric circuit for the proposed OPM, the signal-to-noise ratio (SNR) for the circuit is derived. By analyzing the components that affect the SNR, the amplifier parameters are optimized. As such, a low-noise circuit for the Cs-OPM is developed. The variation of the detection performance due to the lamp power and the radio frequency (RF) power, as well as the cell temperature, is investigated and discussed.

2. Principle of Mx Optically Pumped Cesium Magnetometer

Magnetometers based on magnetic resonance phenomena are divided into Mx and Mz types, classified according to the signals used for the resonance detection. Mx and Mz signals are distinguished according to the projections of the magnetic moment [29]. Mx signals are associated with the transverse component of the magnetic moment and Mz signals are associated with the longitudinal component of the magnetic moment. The sketched view of a single-beam M_x Cs-OPM is shown in Figure 1. A cesium lamp provides pump-light and probe-light sources for the gas-cell. The light passes through the gas-cell and the lens, where the photo detector converts the light signal into the current. Subsequently, the current is converted into a measurable voltage by the amplifier. The feedback network consists of a phase shifter and an automatic gain control (AGC) circuit. The former distinguishes the Larmor frequency and outputs a control signal to make the AGC driving the RF coil in order to establish a self-resonant condition.

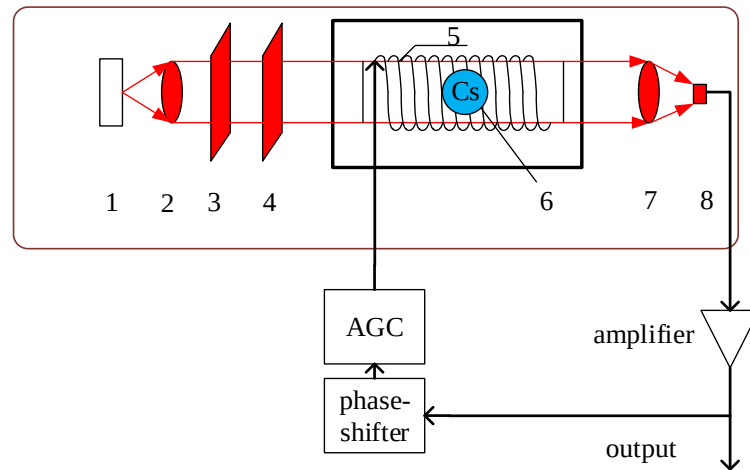


Figure 1. Sketched view of an optically pumped cesium magnetometer with (1) lamp, (2) lens, (3) filter, (4) polarizer, (5) radio frequency (RF) coil, (6) gas cell, (7) lens, (8) photo detector.

Following References [2,10], the sensitivity δB (in T/ $\sqrt{\text{Hz}}$) is expressed as

$$\delta B = \frac{1}{\gamma} \frac{\Gamma}{S/N}, \quad (1)$$

where γ is the gyromagnetic ratio, here, $\gamma \cong 3.5 \text{ Hz/nT}$ for the Cs-OPM, S/N is the SNR of the system with the noise expressed per unit bandwidth, and Γ is the relaxation rate.

For the single-beam M_x magnetometer, the magnetic field provided by the RF coil is parallel to the optical path. The transmitted power $P(t)$ injected to the photo detector can be expressed as [28]

$$P(t) = P_{DC} + P_{IP} \sin \omega_{rf} t + P_{QU} \cos \omega_{rf} t = P_{DC} + P_R \sin(\omega_{rf} t + \phi), \quad (2)$$

$$P_{DC} = P_0(1 - \kappa_0 L + \kappa_0 L \alpha S_{DC}), \quad (3)$$

$$P_{IP} = -P_0 S_0 \kappa_0 L \alpha \frac{(\omega_{rf} - \omega_L) \Omega \sin \theta_B}{(\omega_{rf} - \omega_L)^2 + \Gamma^2 + \Omega^2 \sin^2 \theta_B} \cos \theta_B \sin \theta_B, \quad (4)$$

$$P_{QU} = P_0 S_0 \kappa_0 L \alpha \frac{\Gamma \Omega \sin \theta_B}{(\omega_{rf} - \omega_L)^2 + \Gamma^2 + \Omega^2 \sin^2 \theta_B} \cos \theta_B \sin \theta_B, \quad (5)$$

$$P_R = \sqrt{P_{IP}^2 + P_{QU}^2} = P_0 S_0 \kappa_0 L \alpha \frac{\Omega \sin \theta_B \sqrt{(\omega_{rf} - \omega_L)^2 + \Gamma^2}}{(\omega_{rf} - \omega_L)^2 + \Gamma^2 + \Omega^2 \sin^2 \theta_B} |\cos \theta_B \sin \theta_B|, \quad (6)$$

$$\tan \phi = \frac{P_{QU}}{P_{IP}} = -\frac{\Gamma}{\omega_{rf} - \omega_L}, \quad (7)$$

where, P_{DC} is the DC component, P_{IP} is the in-phase component, P_{QU} is the quadratic component, P_0 is the power of the incident light, κ_0 is the peak absorption cross section, L is the length of the gas cell, α is the multipole analyzing power that depends on the atomic transition with which the light is resonant, S_0 is the equilibrium spin polarization, S_{DC} is the DC component of the polarization, ω_{rf} is the radio frequency, ω_L is the Larmor frequency, Ω is the Rabi frequency, and θ_B is the angle between the incident light and the measured magnetic field.

Figure 2 shows measured line shapes under conditions optimized for maximal sensitivity (see Section 4.4 for details). The measured magnetic field is 53 μT and the Larmor frequency is 185.5 kHz. It can be seen that in the case of self-resonance ($\omega_{rf} = \omega_L$), the in-phase component crosses

the zero point, the quadrature component can reach the maximum amplitude. Thus, the phase difference between the in-phase component and the quadrature component is 90 degrees.

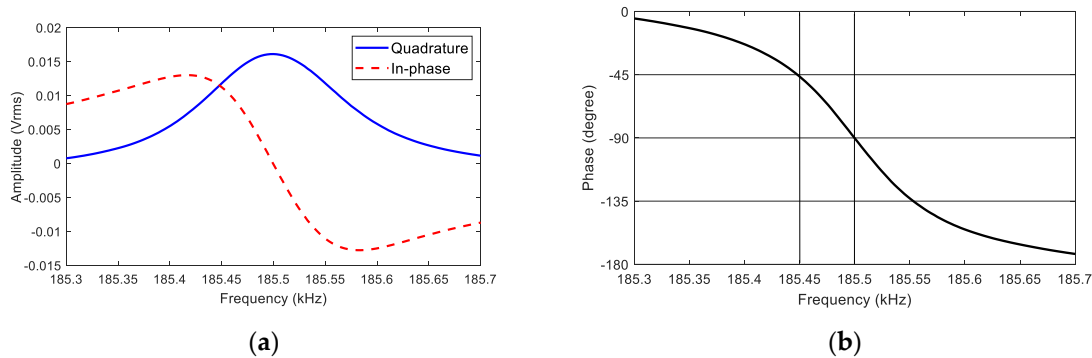


Figure 2. Measured line shapes. (a) Magnetic resonance signal line shapes. (b) Phase line shape.

The schematic diagram of photoelectric detection circuit is shown in Figure 3 [30]. The current amplifier is shown, which consists of a photodiode, a feedback resistor, a feedback capacitor and an operational amplifier. The photodiode is connected with the same polarity of the operational amplifier. R_f and C_f are feedback resistor and capacitor, respectively.

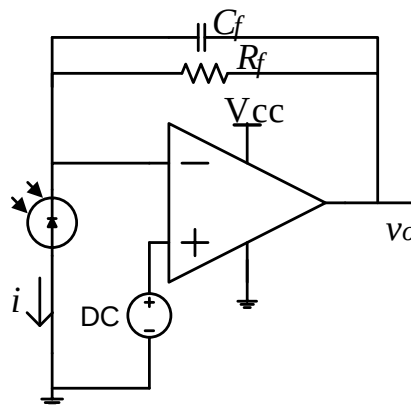


Figure 3. Schematic diagram of the detection circuit.

The current produced by the photodiode can be expressed as [28]

$$i(t) = \eta P(t) = \eta P_{DC} + \eta P_R \sin(\omega_{rf}t + \phi) = I_{DC} + I_{AC}, \quad (8)$$

$$I_{DC} = \eta P_{DC} = \eta P_0(1 - \kappa_0 L + \kappa_0 L \alpha S_{DC}) \propto \eta P_0, \quad (9)$$

$$I_{AC} = I_R \sin(\omega_{rf}t + \phi), \quad (10)$$

$$I_R = \eta P_R = \eta S_0 P_0 \kappa_0 L \alpha \frac{\Gamma \Omega \sin \theta_B}{\Gamma^2 + \Omega^2 \sin^2 \theta_B} |\cos \theta_B \sin \theta_B|, \quad (11)$$

where, η is the sensitivity of the photodiode, I_{DC} is the DC signal, I_{AC} is the AC (alternating current) signal and I_R is the amplitude of the AC signal. In practice, I_{DC} is much larger than I_R . The shot noise of photocurrent is mainly determined by I_{DC} and the Larmor signal at the output is determined by I_R .

The AC current phasor can be written as

$$\dot{I} = I_R e^{j(\phi - 90^\circ)} \quad (12)$$

The voltage phasor generated by the current at the output of the amplifier can be written as

$$\dot{V} = \dot{I}Z_f(f) = I_R Z_f(f) e^{j(\phi-90^\circ)}, \quad (13)$$

where $Z_f(f)$ is the impedance of C_f and R_f in parallel. It yields

$$Z_f(f) = \frac{R_f}{1 + j2\pi f R_f C_f}, \quad (14)$$

So, the output amplitude of the Larmor signal is

$$V_R(f) = I_R Z_f(f) = P_R \eta Z_f(f). \quad (15)$$

3. Noise Analysis and Optimizations of Photoelectric Detection Circuit

3.1. Noise Analysis of Photoelectric Detection Circuit

The equivalent output noise spectral density of the photoelectric detection circuit in Figure 3 can be modeled as shown in Figure 4, where R_i is the equivalent parallel resistance of the photodiode, C_i is the parallel value of the junction capacitance of the photodiode. Besides, the circuit noise sources in Figure 4 consist of the photocurrent shot noise density I_{ns} , the dark current shot noise density I_{nd} , the thermal noise density of feedback resistor I_{nr} , the equivalent input noise voltage density of operational amplifier E_{nop} and the equivalent input noise current density of operational amplifier I_{nop} . Due to the large parallel resistance of photodiodes, the thermal noise generated by the resistance can be ignored compared to the photocurrent and dark current shot noise level, so it is not considered in this paper. The operating range of typical magnetometers for geomagnetic applications is 10,000 nT to 100,000 nT [20–22]. The frequency range of the Larmor signal for cesium magnetometer is 35 kHz to 350 kHz. The $1/f$ noise of the amplifier is not considered either.

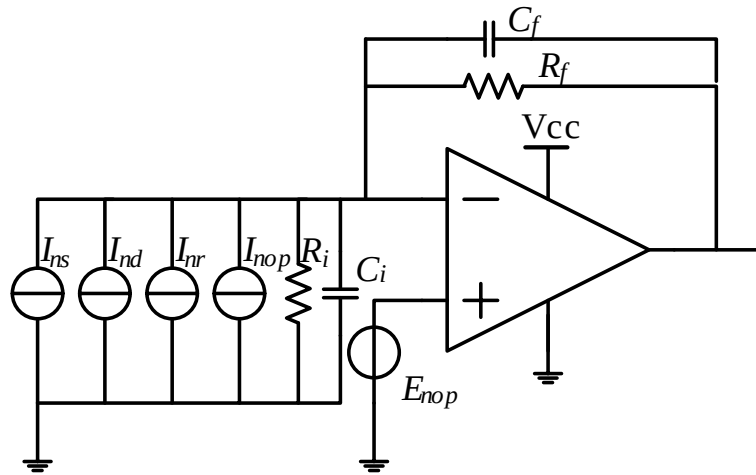


Figure 4. Equivalent noise model of photoelectric detection circuit.

The noise voltage density produced by I_{ns} at the output of the amplifier is

$$E_{ns}(f) = I_{ns} Z_f(f) = \sqrt{2eI_{DC}} Z_f(f), \quad (16)$$

where, e is the electron charge.

The noise voltage density produced by I_{nd} at the output of the amplifier is

$$E_{nd}(f) = I_{nd} Z_f(f) = \sqrt{2eI_d} Z_f(f), \quad (17)$$

I_d is the dark current of the photodiode.

The noise voltage density produced by the feedback resistor at the output is

$$E_{nr}(f) = I_{nr}Z_f(f) = \sqrt{\frac{4kT}{R_f}}Z_f(f), \quad (18)$$

where k is the Boltzmann constant and T is the temperature in Kelvin.

The noise voltage density produced by the equivalent input noise current of the operational amplifier at the output is

$$E_{niop}(f) = I_{niop}Z_f(f), \quad (19)$$

The noise voltage density produced by the equivalent noise voltage of the operational amplifier at the output is

$$E_{neop}(f) = E_{nop}\left(1 + \frac{Z_f(f)}{Z_i(f)}\right), \quad (20)$$

where

$$Z_i(f) = \frac{R_i}{1 + j2\pi fR_iC_i}, \quad (21)$$

As the above five noises Equations (16)–(20) are uncorrelated, the total output noise voltage density is

$$E_{no}(f) = \sqrt{E_{ns}^2 + E_{nd}^2 + E_{nr}^2 + E_{niop}^2 + E_{neop}^2}, \quad (22)$$

From Equations (15) to (22), the output SNR R_{sn} with the noise expressed per unit bandwidth of the photoelectric detection circuit can be obtained by

$$R_{sn}(f) = \frac{|V_R(f)|}{E_{no}(f)} = \frac{1}{\sqrt{R_s^2(f) + R_d^2(f) + R_r^2(f) + R_{iop}^2(f) + R_{eop}^2(f)}}, \quad (23)$$

where

$$R_s(f) = \sqrt{\frac{2eP_{DC}}{P_R^2\eta}}, \quad (24)$$

$$R_d(f) = \sqrt{\frac{2eI_d}{P_R^2\eta^2}}, \quad (25)$$

$$R_r(f) = \sqrt{\frac{4kT}{R_fP_R^2\eta^2}}, \quad (26)$$

$$R_{iop}(f) = \frac{I_{nop}}{P_R\eta} \quad (27)$$

$$R_{eop}(f) = \frac{E_{nop}}{P_R\eta} \left| \frac{1}{Z_f(f)} + \frac{1}{Z_i(f)} \right| = \frac{E_{nop}}{P_R\eta} \left| \frac{R_i + R_f + j2\pi fR_iR_f(C_i + C_f)}{R_iR_f} \right|. \quad (28)$$

It can be seen from above that the output SNR of the photoelectric detection circuit is related to the sensitivity of photodiode, dark current, feedback resistance, amplifier equivalent noise voltage, amplifier equivalent noise current, input resistance, input capacitance, etc. According to Equations (23) and (24), it can be found that an enhanced photo sensitivity η can improve the SNR of the system. From Equations (27) and (28), reducing the equivalent noise voltage and noise current of the amplifier can improve the SNR. However, noise voltage and noise current are inversely related to each other, so it is very important to choose a proper amplifier.

3.2. Optimized Design of Photoelectric Detection Circuit

According to the analysis in the previous section, a higher sensitivity of photodiode can result in a better SNR of the system. The wavelength in the Cs-OPM is about 894 nm. Therefore, the silicon photodiode Hamamatsu S2387-66R is used. Its sensitivity is about 0.55 A/W for the 894 nm wavelength source. Its main parameters are listed in Table 1.

Table 1. Main parameters of S2387-66R.

Parameters	Value
Sensitivity (@ $\lambda=894$ nm), η	0.55 A/W
Terminal capacitance, C_i	4300 pF
Shunt resistance, R_s	10 G Ω
Dark current, I_d	50 pA

The cesium lamp and the atomic gas-cell determine the DC power of the incident light and the signal power at Larmor frequency. In general, the DC power of incident light (P_{DC}) is several hundred microwatts, and the signal power at Larmor frequency (P_R) is about several microwatts. In the model for our case, P_{DC} is 185 μ W, and P_R is 2.4 μ W. The feedback resistance with an optimized value is selected according to the sensitivity of the photodiode, the value of the photocurrent and the supply voltage of the circuit. From the parameters in Equation (9) and in Table 1, one can calculate the value of the DC photocurrent. It yields 0.1 mA. Thus, it should select a feedback resistance R_f of 100 k Ω when the supply voltage is 12 V. According to the feedback resistance, the parameters of the amplifier and the input capacitance, the feedback capacitance C_f of 100 pF is chosen.

When the light power and photodiode are fixed, it is very important to choose a proper amplifier. Table 2 shows several typical low-noise amplifiers with different equivalent voltage and current noise spectral density values. In the following section, the influence of amplifier noise on the total output noise will be calculated.

Table 2. Typical low-noise amplifiers.

	AD549	AD822	AD745	LT1028
equivalent input noise voltage (nV/ $\sqrt{\text{Hz}}$)	35	13	2.9	0.85
equivalent input noise current (fA/ $\sqrt{\text{Hz}}$)	0.11	0.8	6.9	1000

By substituting the circuit parameters in Table 1 and the amplifier noise parameters in Table 2 into Equations (22) and (23), the total output noise and SNR of the circuit with different amplifiers can be obtained. The corresponding model results are shown in Figure 5. It can be seen that in the low-frequency domain, the circuit output noise with different amplifiers shows similar noise levels. However, by increasing the frequency, the difference gradually increases, and the circuit with a lower equivalent noise voltage has better performance. The circuit with LT1028 as the amplifier has the best noise performance and SNR in the full working frequency band.

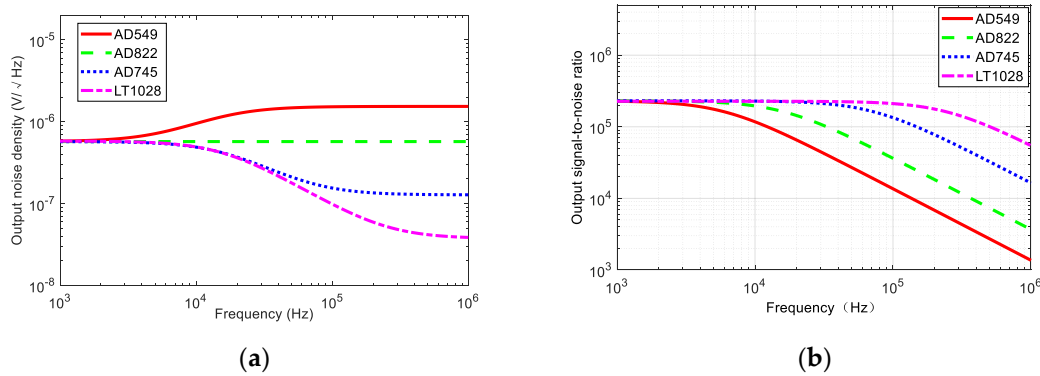


Figure 5. Model results. (a) The output noise voltage density E_{no} of different amplifiers. (b) The output signal-to-noise ratio R_{sn} of different amplifiers.

The noise characteristic is further studied. Taking LT1028 as an example, the noise components of the circuit is modelled and analyzed, and the model results are shown in Figure 6. Due to the large light power, the photocurrent shot noise has a major contribution to the total noise outputs. At low frequencies, the circuit noise is mainly determined by the photocurrent shot noise. As the frequency increases, the amplifier equivalent noise voltage gradually dominates.

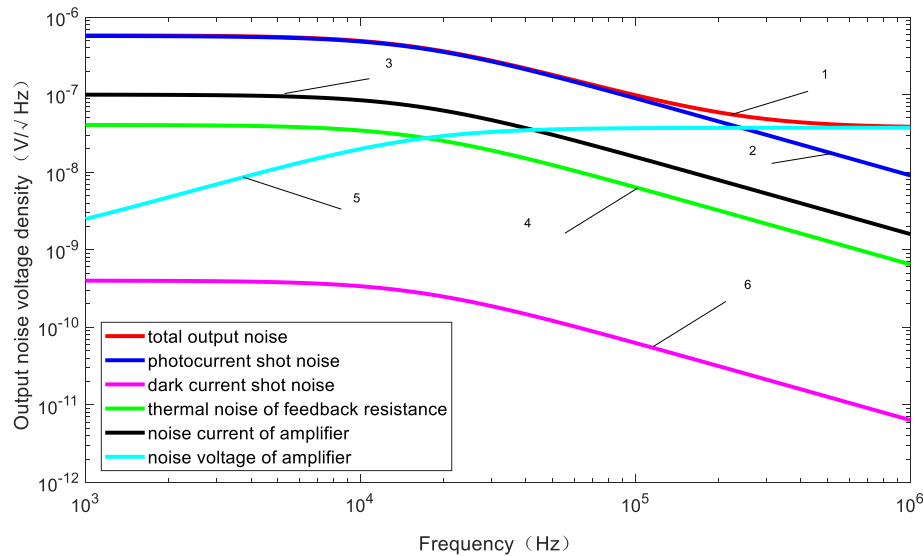


Figure 6. The model results of the noise components voltage density when the amplifier is LT1028: 1. total output noise, 2. photocurrent shot noise, 3. noise current of amplifier, 4. thermal noise of feedback resistance, 5. noise voltage of amplifier, 6. dark current shot noise.

From Figure 6, we can find that in the low frequency band, the effect of equivalent noise current component is greater than noise voltage source of the amplifier. In the high frequency band, it is the opposite. If the effect of photocurrent shot noise is not considered, for low magnetic field measurement, the corresponding Larmor signal is located in the lower frequency band, so the amplifier with low equivalent noise current should be selected. For high magnetic field measurement, such as the geomagnetism case, it will be better to choose an amplifier with low equivalent noise voltage.

4. Experiment and Discussion

The circuit noise is first tested to verify the noise model. Then the parameters of the magnetometer are optimized. The sensitivity of the magnetometer is related to the cell size, buffer gas pressure, cell temperature, incident light power, RF signal power, etc. In this paper, the incident light power,

RF power and the cell temperature are optimized. The cell size is $\phi 25 \times 25$ mm filled with helium as the buffer gas. The experiment setup is shown in Figure 7. We place the magnetometer head inside a multilayer magnetic shield, as shown in Figure 8. A solenoid driven by an ultra-low noise current source produces the magnetic field. The optical axis of magnetometer is with 45 degrees to the direction of magnetic field. A spectrum analyzer “FSV4” is used to measure the SNR of the system, and a lock-in amplifier serves to measure the in-phase component, the quadrature component and the phase curve. Since the magnetometer designed in this paper works in the geomagnetic field range, the optimizations are all obtained in a magnetic field strength of $53 \mu\text{T}$.

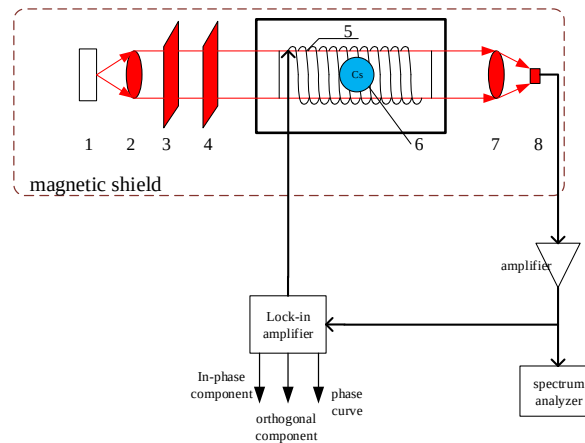


Figure 7. Experiment setup of magnetometer: (1) lamp, (2) lens, (3) filter, (4) polarizer, (5) rf coil, (6) cell, (7) lens, (8) photo detector.

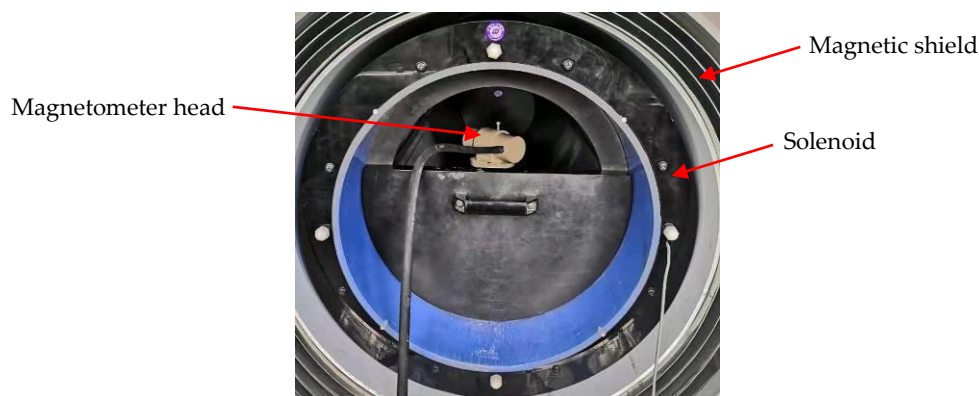


Figure 8. Photo of the experimental set-up.

4.1. Test of Photoelectric Detection Circuit

The photoelectric detection circuit, as shown in Figure 9, is developed by using the LT1028 as the core and its noise characteristic is tested by the spectrum analyzer “FSV4”. The results are shown in Figure 10. Figure 10a are the results without incident light. The circuit is placed in the dark environment so that the circuit noise is mainly dominated by the equivalent noise voltage and equivalent noise current of the amplifier. Figure 10b show the results when the incident light power is $185 \mu\text{W}$. At this condition, the circuit noise is mainly dominated by the photocurrent shot noise, the equivalent noise voltage and the equivalent noise current of amplifier. The experimental results are in good accordance with the model.



Figure 9. Photo of the electronic unit.

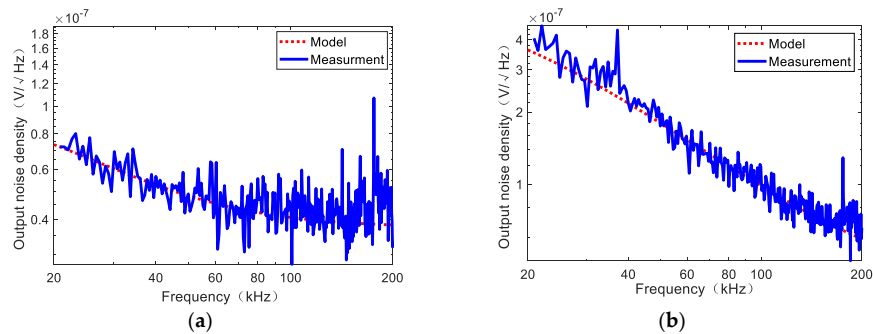


Figure 10. Comparison of modelled and measured results of output noise as a function of frequency. (a) Output noise without incident light. (b) Output noise with incident light.

4.2. Optimization of RF Power

The RF power corresponds to the RF magnetic field. The Rabi frequency Ω is proportional to the RF magnetic field. From Equation (11), when the RF power (the Rabi frequency) increases, the signal amplitude reaches a maximum value. In this case, the sensitivity of the magnetometer can be optimized. In our experiments, the RF magnetic field is produced by a solenoid connected in series with a resistance and a voltage source. The RF magnetic field is changed by changing the output of the voltage source. The measured amplitude of the Larmor signal and the output noise floor varying with the amplitude of RF signal are shown in Figure 11. When the amplitude of RF signal increases from small values to larger ones, the signal amplitude increases first and then decreases. Thus, by optimizing the parameters, the maximum signal amplitude can be found. As the noise and relaxation rate are independent of the RF power [10,28], the output SNR and the sensitivity are the best when the signal amplitude reaches the maximum. The measurements of the output noise floor and the output SNR are shown in Figure 11b,c.

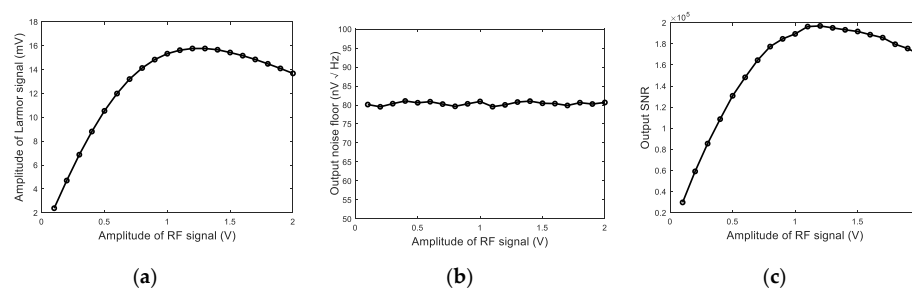


Figure 11. The measured amplitude of the Larmor signal, the output noise floor and the output signal-to-noise ratio (SNR) varying with the amplitude of RF signal. (a) The measured amplitude of the Larmor signal. (b) The output noise floor. (c) The output SNR.

4.3. Optimization of Incident Light Power

Incident light power affects the Larmor signal amplitude, the noise level, and the relaxation rate. Increasing the incident light power can increase the Larmor signal amplitude, but the relaxation rate and noise level also increase [10,28]. At the same time, noise level is not only related to the incident light power, but also related to the noise of the amplifier. It is difficult to find the optimal incident light power value with a simple formula, so the parameter needs to be optimized by experiments. In the experiment, the output DC voltage of the photoelectric detection circuit is used to determine the incident light power. As mentioned in Section 4.2, the noise and relaxation rate are independent of the RF power. Under the condition of each incident light power, the relaxation rate and the noise are measured. The relaxation rate is obtained from the phase curve. In the case of $\omega_{rf} - \omega_L = \Gamma$, the phase difference is 45 degrees. The RF power is optimized, and the maximum Larmor signal amplitude is used to calculate the sensitivity at each incident light power point. The measured results are shown in Figure 12. All the data are obtained when the cell temperature keeps at 35 °C. Through the experiment, the incident light power with the best sensitivity is obtained.

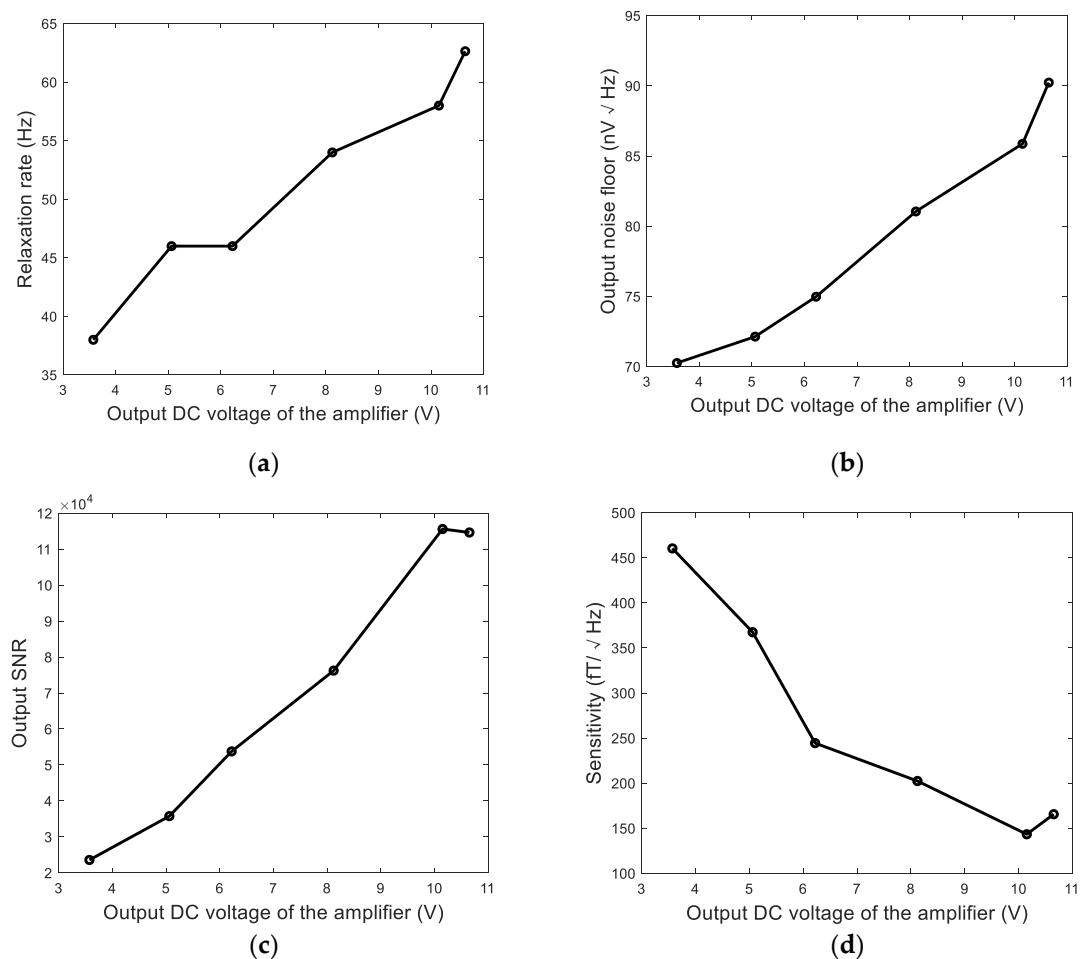


Figure 12. (a) Result of the relaxation rate changing as a function of the output DC voltage of the amplifier. (b) Result of the output noise floor changing as a function of the output DC voltage of the amplifier. (c) Result of the output SNR changing as a function of the output DC voltage of the amplifier. (d) Result of the sensitivity changing as a function of the output DC voltage of the amplifier.

4.4. Optimization of Cell Temperature

Both the relaxation rate and signal amplitude of the magnetometer are affected by the cell temperature. By increasing the cell temperature, the atomic density in the cell and signal amplitude increases, but the relaxation rate can also increase [31]. Generally, it is necessary to find the best cell temperature through an experimental method. Under the condition of each cell temperature, the incident light power and RF power are optimized by the method mentioned in Sections 4.2 and 4.3. Theoretically, the noise level does not change with the cell temperature. However, in our experiment, the noise level and the sensitivity at each temperature point are obtained from the optimized light power and RF power. As the optimal optical power is different at different cell temperatures, the noise level is also different. The experimental results are shown in Figure 13. It shows that the magnetometer has the high sensitivity when the cell temperature is around 55 °C.

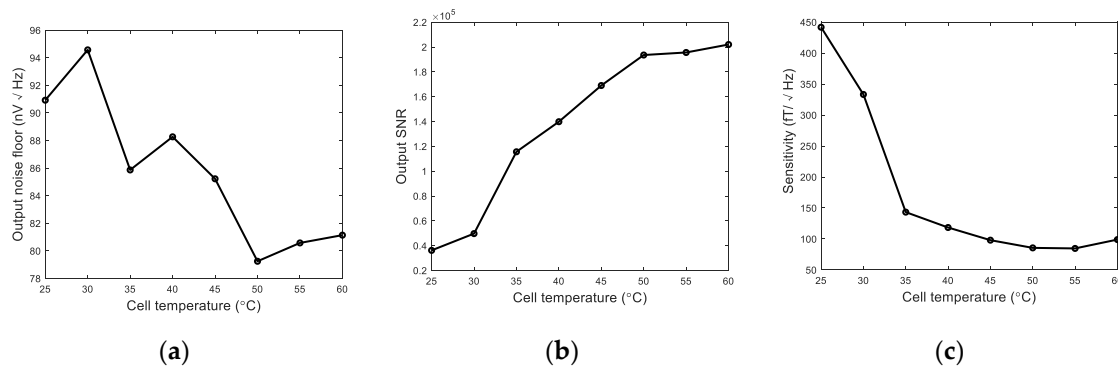


Figure 13. (a) Result of the output noise floor changing with the cell temperature. (b) Result of the output SNR changing with the cell temperature. (c) Result of the sensitivity changing with the cell temperature.

Through optimization, the optically pumped magnetometer designed in this paper has a relaxation rate of 58 Hz. The measured amplitudes and phases near the resonant frequency are shown in Figure 2. The red line indicates the in-phase signal line shape and the blue one indicates the quadrature signal line shape. Figure 14 shows the measured noise voltage density. The white-noise floor far from the resonant frequency represents the intrinsic noise level. The contributions from fluctuations of the magnetic field (produced by the current source and external environment) make the noise floor near resonant frequency higher. In Figure 14, The resolution bandwidth is set to 1 Hz. The signal amplitude is 15.76 mV and the white-noise floor is about 80 nV. Thus, the intrinsic SNR is about 197,000. By substituting these parameters into (1), the intrinsic sensitivity of 85 fT/√Hz is obtained.

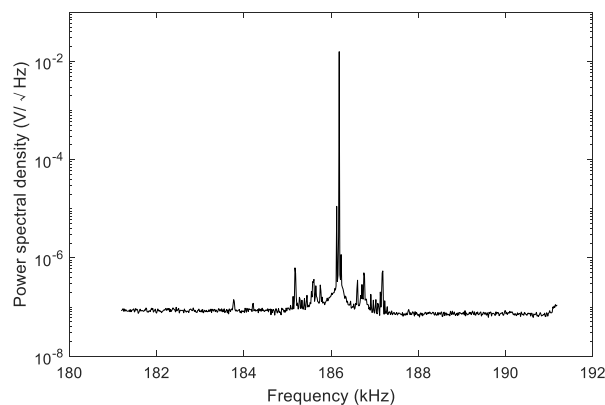


Figure 14. Root power spectral density measured by FSV4.

5. Conclusions

This paper analyzes the noise characteristics of the photoelectric detection circuit in the frequency domain for a cesium optically pumped magnetometer. Considering the characteristics of the photodiode and the associated operational amplifier, the equivalent noise of the low-noise pre-amplifier detection circuit is calculated. The results have good accordance with the measurements. The calculations can serve to guide the low-noise circuit design. The influences of the RF power, the incident light power and the cell temperature are also investigated and improved. With the help of all the mentioned optimizations, a single-beam optically pumped cesium magnetometer with a sensitivity of lower than 100 fT/ $\sqrt{\text{Hz}}$ is realized in a 53 μT magnetic field condition, which is suitable for geomagnetism applications.

The optimizations in this paper can serve to improve the detection performances for all the optically pumped magnetometers with a photodiode and current amplification process, not limited to the ones with cesium source. According to the frequency band of the Larmor signal, the appropriate photodiode and low-noise amplifier can be chosen for the optimization. For the other types of optically pumped magnetometers, the optimization process in this manuscript is also applicable.

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