Low Noise VCSEL Driver for SERF Atomic Magnetometer

Feihu Wang\textsuperscript{1,2}, Zhaohui Hu\textsuperscript{1,2,3,4,a} and Xin Liu\textsuperscript{1,2}

\textsuperscript{1} School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing 100191, China
\textsuperscript{2} Science and Technology on Inertial Laboratory, Beihang University, Beijing 100191, China
\textsuperscript{3} Research Institute of Frontier Science, Beihang University, Beijing 100191, China
\textsuperscript{4} Beijing Advanced Innovation Center for Big Data-Based Precision Medicine, Beihang University, Beijing 100191, China
\textsuperscript{a} huzh@buaa.edu.cn

Abstract. A new type of VCSEL (Vertical-Cavity Surface-Emitting Laser) which uses Pt1000 as a temperature sensitive component and non-magnetic heating membrane as a temperature actuator is designed for SERF (Spin-Exchange Relation-Free) atomic magnetometer, which can decrease the magnetic interference produced while heating or cooling VCSEL. Therefore a low noise driver for this kind of VCSEL is necessary. A driver for the novel VCSEL is designed in this paper. The output current is adjustable from 0 to 4.5 mA, and RMS (Root Mean Square) noise of current is less than 80 nA. The operating temperature of the VCSEL is adjustable between 30-110 ℃ and RMS noise of temperature is less than 0.6 mK. So that it can be ensured that the VCSEL outputs a laser with stable optical power and wavelength.

1. Introduction
High sensitivity magnetometry is demanded in many fields, such as biology, geology, and medical science\cite{1}. Traditionally those applications is enabled by superconducting quantum interference device (SQUID) magnetometer\cite{2, 3}. But in the recent years SERF (Spin-Exchange Relation-Free) magnetometer has been demonstrated and achieved a magnetic field sensitivity of 0.16fT/√Hz \cite{1}. SERF magnetometer also opens the possibility of detecting magnetoencephalogram (MEG) and magnetocardiogram (MCG) with array of ultrahigh sensitivity magnetometers. In the operating of SERF magnetometer, laser is required to optically pump the gaseous alkali-metal atom in the cell and detect its polarization. VCSEL (Vertical-Cavity Surface-Emitting Laser) is often used to play the role. But the noise of wavelength and optical power can highly reduce the sensitivity of SERF magnetometer, which requires a low noise VCSEL driver.

VCSEL driver often contains two parts, stable current driver and temperature control system. For the current driver, there have been a lot of commercial products, such as LD1255R of Thorlabs company which has a ripple current smaller than 1 μA, Newport company’s LDX-3210 with 2 μA, and Wavelength company’s MPL-250 with 1 μA. For the temperature control system, commercial product can also be found. For example, Thorlabs company’s TED200C temperature control system can achieve the temperature stability of 2 mK, so does Wavelength company’s LFI-3751, Newport company’s LDT-5910C-120V can even achieve 1 mK. Those advanced commercial products is stable enough for
SERF magnetometer, however, it is hard to integrate these commercial products into compact SERF magnetometer control system because of their big sizes and incompatibility. And TEC (Thermoelectric Cooler) is often used to cool and heat in the temperature control system which can generate extra magnetic interference because of its large current. The extra magnetic interference will make it hard to keep the high sensitivity of SERF magnetometer. So it is more proper to heat VCSEL with the special non-magnetic heating membrane for SERF magnetometer.

In this paper we present a low noise VCSEL driver, which also contains current driver and temperature control system. For the current driver, the current can be tuned between 0 mA and 4.5 mA which can satisfy most VCSEL, and RMS noise of current is no more than 80 nA. For temperature control system, the non-magnetic heating membrane is used to heat the new VCSEL, temperature can change between 30°C and 110°C, and RMS noise of temperature is no more than 0.6 mK. Besides its interface for FPGA can easily be transplant into the control system of SERF magnetometer and magnetic interference produced by VCSEL can be highly reduced. The theory of VCSEL including the relation between current, operating temperature, wavelength and optical power of VCSEL will be discussed. Then we will describe the design of VCSEL driver, key technology and how it works. In the end experiments will be set up to check the performance of VCSEL driver and measure the stability of current and operating temperature.

2. Theory

The wavelength and optical power of VCSEL beam is highly affected by current flowing through VCSEL. Operating temperature of VCSEL can change the concentration of electron in the optical resonant cavity, the feature of optical resonant cavity and the threshold current, which in the end will also affect the wavelength and optical power of VCSEL. So it is feasible to achieve low-noise optical beam by making the current and operating temperature stable enough. In the following parts of this section, we will discuss the relation between wavelength, optical power, current and operating temperature.

The relation between current and optical power features like Fig. 1. When the current is less than threshold current, the optical power of VCSEL slowly increases with the current, which is mainly caused by spontaneous radiation. When the current is larger than threshold current, the optical power \( P \) of VCSEL has a linear correlation with current \( I \), which is shown in Eq.1,

\[
P = \eta_d \frac{h\nu}{q} (I - I_{\text{th}}), \quad (I > I_{\text{th}}).
\]  

Where \( \eta_d \) is external differential quantum efficiency of VCSEL; \( h \) is Planck constant; \( \nu \) is the frequency of laser and \( q \) is unit charge.

![Fig. 1 The correlation between current and optical power](image-url)
With the increasing of operating temperature, external differential quantum efficiency $\eta_d$ decreases and threshold current get larger, which makes optical power of VCSEL smaller. So the optical power has a negative correlation with operating temperature.

Operating temperature can also affect the wavelength of VCSEL, higher temperature will make the wavelength larger. During the operation of VCSEL, more Joule heat will be produced with larger current, which equals to the increasing of operating temperature. Therefore larger current will move wavelength to the ‘red side’ (larger wavelength).

In most datasheets of VCSEL, the relation between current, operating temperature and wavelength is simplified to wavelength temperature coefficient and wavelength current coefficient. The relation between current, operating temperature and optical power is also approximately linear and it can be simplified to optical power temperature coefficient and optical power current coefficient which can be obtained through experiments. All the coefficients of VIXAR’s 795 nm VCSEL is shown in Table 1.

Table 1 All coefficient of VIXAR’s 795 nm VCSEL

| Parameter                        | Typical       | Units        |
|----------------------------------|---------------|--------------|
| Wavelength Temperature Coefficient | 0.055(from datasheet) | nm/K         |
| Wavelength Current Coefficient   | 0.3(from datasheet) | nm/mA        |
| Optical Power Temperature Coefficient | $-4.1\times10^{-3}$ (from experiment) | mW/K         |
| Optical Power Current Coefficient | 0.324(from experiment) | mW/mA        |

3. Design of VCSEL Driver

VCSEL driver contains host computer system, FPGA software and hardware circuit. Figure 2 shows the block diagram of VCSEL driver. Host computer system is used to control the operating state of VCSEL such as current size, operating temperature and PID parameters. The setting command from host computer will be sent to FPGA, in which commands is transformed into electrical control signal. After receiving the electrical control signal from FPGA, hardware circuit generates the current for VCSEL and keeps the operating temperature which is set from host computer system.

3.1 Host Computer System

Host computer system is designed for user to control the operating state of VCSEL easily, in which current, operating temperature, sample frequency and PID parameters are set. And it is easy to monitor the actual operating state of VCSEL. Figure 3 shows the interface of host computer system.
3.2 FPGA

In order to be easily transplanted into the whole control system of SERF atomic magnetometer, a commercial FPGA development board is used to control the VCSEL driver instead of a FPGA core in the hardware circuit. Only the proper interfaces are needed from SERF atomic control system, can VCSEL driver be easily integrated into the whole system. FPGA software is used to accept the control command from host computer system through module UART_RX, and the packaged control command is checked and distributed to DAC8830 driver to generate control signal of current and temperature. And the operating state of current and temperature is collected by ADS1248 driver, which is packaged and uploaded to host computer system through module UART_TX.

3.3 Hardware Circuit

The hardware circuit comprises power source, current driving circuit and temperature control circuit which are shown in Fig. 5. The power source circuit is used to generate the voltage of ±18V, ±12V, ±5V, ±24V and ±15V, which will be used in other parts of circuit. The current driving part can be divided into a digital-to-analog circuit, voltage-controlled current source circuit, protective circuit, signal processing before ADC and analog to digital circuit. The temperature control circuit includes analog to digital circuit which is used to obtain the temperature, a digital to analog circuit and two-stage amplifying
circuit which is used to heating the membrane. Then, the principle and function of some key parts will be described in detail.

![Block diagram of hardware circuit](image)

Fig. 5 Block diagram of hardware circuit

The digital-to-analog circuit uses DAC8830 to convert the digital control signal into an analog voltage. The DAC8830 is a 16-bit digital-to-analog converter with low noise and an integral nonlinearity error of 1LSB. In order to further reduce the noise of the DAC8830 output voltage, a low-pass filter is added in front of the power supply port, and a low-pass filter is added to the back end of the analog voltage output port, which enables the DAC8830 to output a more stable control voltage. The circuit diagram is shown in Fig. 6.

![Digital-to-analog circuit of current driver](image)

Fig. 6 Digital-to-analog circuit of current driver

The voltage-controlled current source circuit is implemented by a bipolar junction transistor. Based on the voltage-controlled current source in Ref. [4], some improvements have been made because VCSEL requires less current but higher stability [5]. The circuit diagram is shown in Fig. 7. The output current $I_{DC}$ is proportional to the control voltage $V_{control}$.

$$I_{DC} = \frac{\beta_1}{1 + \beta_1} \times \frac{\beta_2}{1 + \beta_2} \times \frac{R_2}{R_3R_4} \times V_{control},$$  \hspace{1cm} (2)
where $\beta_1$ is the current gain of the transistor Q1, $\beta_2$ is the current gain of the transistor Q2. According to the characteristics of the transistor, it can be known that $\beta_1$ and $\beta_2$ are much larger than 1, and $R_2$ equals to $R_3$ in the design. The above formula can be simplified to

$$I_{DC} = \frac{V_{control}}{R_4}.$$  \hspace{1cm} (3)

The output current is only related to the control voltage. The control voltage is up to 5V (full-scale output of the DAC8830), while the maximum current required by the VCSEL does not exceed 4.5mA, usually about 2mA. So the resistance can be obtained from Eq. 4.

$$R_4 = \frac{V_{control}}{I_{dc\_max}} = \frac{5V}{0.0045A} = 1111.1\Omega.$$  \hspace{1cm} (4)

In order to ensure the normal operation of the VCSEL, a protective circuit is added behind voltage-controlled current source circuit[6]. The circuit diagram is shown in Fig. 8. When the power is turned on, the output current does not instantaneously increase to the set current, but slowly increases, which achieve the effect of soft start; when the circuit suddenly loses power, the current on the laser does not directly drop to 0, but slowly decreases, which achieve the effect of shutdown protection.
monitoring process does not affect the output current, a voltage follower is added to isolate two parts. To improve the detection accuracy, a differential amplifying circuit is added to improve the signal-to-noise ratio of the detection signal. And a second-order Butterworth filter is added to avoid aliasing error during DAC conversion. Then ADS1248 converts analog signal into a digital signal, which is uploaded to the host computer system through the FPGA to display the current in real time. These parts are shown in Fig. 9.

Fig. 9 Signal processing before ADC

The temperature control system includes analog-to-digital circuit, digital-to-analog circuit and two stage amplifying circuit. The analog-to-digital circuit is shown in Fig. 10. ADS1248 is used to collect the resistance value of PT1000 which can be used to calculate the temperature[7]. In order to reduce the influence of current drift on the acquisition accuracy, the reference voltage of ADS1248 is generated by constant current and high-precision resistance. PT1000 is also connected to the high-precision resistance[8].

Fig. 10 The diagram of analog to digital circuit

The required heating voltage signal is generated after the calculation of host computer system with PID algorithm[9]. Then it is transmitted to the circuit board through the FPGA and converted into an analog voltage after DAC8830. Since the heating power required for the non-magnetic heating membrane is relatively large, it is necessary to pass through a two-stage amplifying circuit to amplify the signal and increase the carrying capacity. Process block diagram of heating voltage signal is shown in
Fig. 11. The amplified heating signal is then applied to both ends of the non-magnetic heating membrane for heating VCSEL.

Fig. 11 Process block diagram of heating voltage signal

4. **Experiment Setup and Results**

An experiment setup is built to test the performance of VCSEL driver. Because the VCSEL with PT1000 and non-magnetic heating membrane is currently in the process of production, a traditional VCSEL is used to test the current stability. In addition, non-magnetic heating membrane and PT1000 are adhered together through silica gel to test the stability of temperature control system.

4.1 *Test the stability of current*

Different current values have been set from the host computer. A high-precision multimeter is connected to the current output to collect the current value within 30 minutes. The actual current data when set current is 3mA is displayed in Fig. 12.

Fig. 12 The actual current data when set current is 3mA

After analyzing current data, mean value and RMS noise of actual current are shown in Table 2. It can be seen that the output current is adjustable within 0-4.5 mA, and the mean value of the output current differs little by the set current, which are less than 0.032 mA. The RMS noise is less than 0.08 μA.
### Table 2 The result of current experiments

| Set current [mA] | Mean value of actual current [mA] | Deviation between set current and mean value [mA] | RMS noise of current [μA] |
|------------------|----------------------------------|--------------------------------------------------|--------------------------|
| 0                | 0.00030                          | -0.0003                                         | 0.02                     |
| 0.5              | 0.49679                          | 0.00321                                         | 0.003                    |
| 1                | 0.99338                          | 0.00662                                         | 0.006                    |
| 1.5              | 1.48982                          | 0.01018                                         | 0.04                     |
| 2                | 1.98639                          | 0.01361                                         | 0.06                     |
| 2.5              | 2.48298                          | 0.01702                                         | 0.07                     |
| 3                | 2.97947                          | 0.02053                                         | 0.04                     |
| 3.5              | 3.47584                          | 0.02416                                         | 0.05                     |
| 4                | 3.97209                          | 0.02791                                         | 0.06                     |
| 4.5              | 4.46835                          | 0.03165                                         | 0.08                     |

In order to determine the long-term stability of the current driver, the output current is set to 1.5 mA for 10 consecutive hours. The actual current in the 10 hours is displayed in Fig. 13. It can be seen that the RMS noise of the output current is less than 0.04 μA, and the drift of current is very small.

![Long-term stability of current when set current is 1.5mA](image)

**Fig. 13 Long-term stability of current**

### 4.2 Test the accuracy of temperature detection

The stability of the temperature measurement is the premise for stable temperature control. And temperature is measured by detecting the resistance of PT1000. Then the resistance is reflected into temperature value. Therefore, the stability of the resistance measurement is directly related to the stability of the temperature control system. Here we use a 1kΩ resistor with an accuracy of 0.01% and a temperature drift of 1 ppm as a standard component to test the stability of the temperature acquisition. The acquired data of standard resistance within 30 minutes is displayed in Fig. 14. It can be seen that for 1kΩ resistances, the resistance acquisition RMS noise is less than 1.3 mΩ. Because the coefficient between resistance and temperature of PT1000 is 3.9 Ω/K, the noise of resistance acquisition can be reflected to the temperature acquisition RMS noise of 0.33 mK, which is stable enough for VCSEL driver.
4.3 Test the stability of temperature control

After checking the RMS noise of temperature acquisition, the non-magnetic heating membrane and the PT1000 are glued together to test the temperature control system for the VCSEL. Different temperatures are set from host computer system and temperature data is also acquired by host computer system. Each set temperature lasts for 30 minutes. The mean value and RMS noise of actual temperature are listed in Table 3.

Table 3 The stability of temperature control

| Setting temperature (°C) | Mean value of actual temperature (°C) | RMS noise of temperature (mK) |
|-------------------------|--------------------------------------|-------------------------------|
| 30                      | 29.9999                              | 0.4                           |
| 50                      | 49.9999                              | 0.5                           |
| 70                      | 70.0000                              | 0.5                           |
| 90                      | 90.0000                              | 0.6                           |
| 110                     | 109.9999                             | 0.5                           |

It can be seen that the operating temperature can change between 30-110°C and RMS noise of the temperature control system is within 0.6 mK.

4.4 Predict the RMS noise of optical power and wavelength

According to the coefficients in Table 1, the RMS noise of optical power and wavelength can be predicted assuming the novel VCSEL has the same coefficients with VIXAR’s 795 nm VCSEL. Because the noise from current and operating temperature is independent of each other, the RMS noise of optical power $N_{power}$ and wavelength $N_{wavelength}$ can be obtained from Eq. 5 and Eq. 6,

$$N_{power} = \sqrt{(N_{current} \times C_{current\_power})^2 + (N_{temperature} \times C_{temperature\_power})^2}.$$  \hspace{1cm} (5)

$$N_{wavelength} = \sqrt{(N_{current} \times C_{current\_wavelength})^2 + (N_{temperature} \times C_{temperature\_wavelength})^2}.$$  \hspace{1cm} (6)

where $N_{current}$ is the RMS noise of current and $N_{temperature}$ is the RMS noise of operating temperating. $C_{current\_power}$ means the coefficient between current and optical power, $C_{temperature\_power}$ means the
coefficient between operating temperature and optical power. \( C_{\text{current \_ wavelength}} \) is the coefficient between current and wavelength. \( C_{\text{temperature \_ wavelength}} \) is the coefficient between temperature and wavelength. The predicted RMS noise of optical power is 0.026 mW and RMS noise of wavelength is \( 4.08 \times 10^{-5} \) nm according to Eq. 5 and Eq. 6.

5. Conclusion
For higher sensitivity of SERF atomic magnetometer we demonstrated a low noise driver for a new type of VCSEL that uses PT1000 as temperature sensitive component and non-magnetic heating membrane as the temperature actuator. The driver contains two parts: current driver and temperature control system. The current driver can generate a current of 0-4.5mA and the current RMS noise is less than 80nA. The effect of soft start and shutdown protection can be realized, so that the VCSEL can work safely. The temperature control part realizes that the operating temperature is adjustable between 30-110 °C, and temperature RMS noise is within 0.6 mK, which can meet the requirements of VCSEL for SERF atomic magnetometers.

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