Temperature control circuit design of high-precision laser diode based on type III compensation network

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Abstract: Since the performance of laser diodes is sensitive to ambient temperature, thermoelectric cooler temperature control circuits based on standard PID temperature compensation networks are usually designed to achieve diode constant temperature control. The thermoelectric cooler time constant and thermistor thermal time constant introduced in the temperature control system will reduce the stability margin of the system. In view of this, this paper designed a high-precision laser diode temperature control circuit based on the type III compensation network, and established the transfer function model, optimized the compensation network parameter tuning method, made the phase margin of the temperature control system reach \( \pi/8 \), and the long-term temperature control accuracy was better than 3 mK in the ambient temperature range of 5 to 40 °C.

1. Introduction
The performance of the semiconductor laser diode (SLD) is extremely sensitive to temperature, and the typical wavelength drift coefficient caused by temperature is close to 0.3 nm/°C [1], so high-precision constant temperature control is indispensable for the SLD. At present, the 24-hour temperature control accuracy of the laser drive equipment manufacturing companies such as ILX Lightwave, Wavelength Electronics, and ALPHALAS in Germany are all better than 3 mK. However, due to the wide coverage of its temperature control system and the different models of thermoelectric coolers (TEC) and thermistors (NTC), it is difficult for the PID parameters tuned under a specific mathematical model to be universal. For this reason, domestic and foreign researchers have conducted research on laser diode temperature control circuits. As a temperature control microchip specially used for TEC module control, max1978 has the characteristics of high temperature control accuracy, simple peripheral circuits, low ripple, and low noise [2]. He Chiguang of Huazhong University of Science and Technology, Que Yan of University of Electronic Science and Technology, Cao Yanchang of North University of China and other scholars used max1978 chip to design laser diode temperature control circuit [3~5]. Among them, the temperature control circuit designed by North University of China has the best temperature control performance and the best temperature control accuracy can be 4 mK. Based on the type III compensation network [6] and using max1978 chip, this paper designed a laser diode temperature control circuit, established a mathematical model of the temperature control circuit transfer function, and through methods of compensating the NTC/TEC pole frequency caused by the phase shift and increasing the phase margin of temperature control system, we optimized the type III compensation network parameters to make the long-term temperature control accuracy of the temperature control circuit better than 3 mK in the ambient temperature range of 5 to 40 °C.
2. SLD temperature control circuit design

2.1 SLD temperature control principle

The principle of SLD temperature control is shown in Fig. 1: The H-bridge circuit converts the SLD setting temperature and the SLD operating temperature induced by the NTC into a voltage signal and transmits it to a differential amplifier circuit with a gain of 50 times. The differential amplifier circuit compares the current temperature voltage signal with the set point temperature voltage to generate a voltage difference. Type III compensation network compensates the phase delay caused by TEC and NTC according to the deviation voltage. At the same time, the output signal of the compensation network is sent to the PWM controller to drive the H-bridge circuit to control the current characteristics of the TEC, and finally the SLD temperature tends to the set temperature.

![Figure 1 Schematic diagram of temperature control](image)

2.2 SLD constant temperature control circuit design

The SLD constant temperature control circuit is composed of five parts: H-bridge temperature sensing circuit, type III compensation network, TEC display circuit, high and low temperature alarm circuit, and TEC current limiting circuit.

The H-bridge temperature sensing circuit is shown in Fig. 2. The sliding rheostat is used to set the temperature, and the thermistor is used to detect the TEC temperature in real time. The temperature set value and the monitored temperature are converted into voltage and input through the FB+ and FB- pins.

![Figure 2 H-bridge temperature sensing circuit](image)

The function realized by the high and low temperature alarm circuit is that when the temperature difference between the set temperature and the TEC temperature exceeds 1.5 °C, the LED will light up to display. The TEC current limiting circuit is mainly used to limit the TEC maximum voltage and maximum positive and negative current values.

2.3 Type III compensation network

A resistor $R_{14}$ and a capacitor $C_{11}$ are added on the standard PID adjustment circuit, such a controller is called a type III compensation network [7], as shown in Fig. 3.
The transfer function is:

\[ G(s)_{\text{TYPE III}} = \frac{R_{14} + R_{15}}{R_{14} R_{15} C_{11}} \times \left( s + \frac{1}{R_{13} C_{9}} \right) \left( s + \frac{1}{R_{14} C_{10} + R_{15} C_{10}} \right) \times \frac{1}{s^2 + \frac{C_{9} + C_{10}}{R_{13} C_{11} C_{10}} (s + \frac{1}{C_{10} R_{14}})} \]  

(1)

The transfer function has two negative real zero frequencies, two negative real pole frequencies, and an initial pole frequency, in which the zero frequency introduces phase lead, and the pole frequency introduces phase lag [7]. Optimizing the parameters of the type III compensation network can enhance the compensation effect of the network zero frequency on the NTC/TEC pole frequency phase shift, increase the phase margin of the temperature control system, and let the system trade-off between stability, response speed and control accuracy achieve optimal matching.

3. TEC heat dissipation and heat shielding design

3.1 TEC heat dissipation design

To use TEC to control the temperature of SLD, it is necessary to dissipate the heat conducted from SLD to TEC. The heat dissipation capacity of TEC is related to the thermal resistance \( h_{a-b} \) from the hot end to the environment. Studies have shown that there is a maximum limit value of \( h_{a-b} \) in the process of TEC refrigeration, and only when \( h_{a-b} \) is less than this limit value, the refrigerator can perform the cooling function [8].

The connection of the rectangular fin radiator with the TEC can increase the convective heat transfer coefficient at the cold end of the refrigerator, reduce the thermal resistance, and enhance the heat dissipation capacity. The SLD heat dissipation structure is shown in Fig. 4 [9]. SLD, TEC, and radiator are connected by the contact surface coated with thermally conductive silicone grease. On the one hand, it reduces the surface contact thermal resistance and facilitates heat transfer. On the other hand, it can play a buffer role to avoid crushing the refrigerator due to uneven force on the screws [8].

![Figure 4 Rectangular fin radiator for TEC heat dissipation design](image)

After the SLD is thermally shielded, the convective heat transfer coefficient of the radiator decreases, and the heat capacity of the radiator is small due to the limited volume and quality of the radiator. Therefore, after the SLD is thermally shielded, the small-volume, low-quality rectangular fin radiator cannot meet the heat dissipation requirements of the TEC. A large-volume aluminum block is selected as the TEC heat sink, and the heat capacity of the TEC heat sink is increased by increasing the volume...
and mass of the aluminum block to improve the heat dissipation capacity of the TEC cold end. The structure is shown in Fig. 5 [10].

Figure 5 Aluminum block heat dissipation design for TEC

3.2 TEC heat shield design
The ambient temperature will affect the refrigeration capacity and refrigeration coefficient of TEC [11]. To reduce the influence of ambient temperature, a thermal shielding layer is designed to shield the SLD and TEC. At the same time, the thermal shielding layer acts as a heat sink of the TEC to conduct heat from the cold end of the TEC to the surrounding environment. The structure is shown in Fig. 6. The material selection, thickness and volume of the heat shielding layer all affect the heat shielding effect.

Figure 6 Laser diode thermal shielding structure

4. SLD temperature control system control model

4.1 Mathematical model of temperature control system
The SLD temperature control process is shown in Fig. 7. NTC is used as a temperature sensor to collect the TEC temperature. The H bridge circuit inputs the NTC temperature and the set temperature, and then inputs to the type III compensation network through the differential amplifier circuit, driving the H bridge circuit to control the magnitude and direction of the TEC current to make the TEC temperature close to the set temperature, thereby gradually reducing the temperature difference between the set temperature and the NTC, and finally make the set temperature the same as the TEC temperature.

The closed-loop transfer function of the temperature control system is:

$$G_c(s) = \frac{K \times G_{\text{TEC}}(s) \times H_{\text{TEC}}(s) \times H_{\text{NTC}}(s)}{1 + K \times G_{\text{TEC}}(s) \times H_{\text{TEC}}(s) \times H_{\text{NTC}}(s)}$$

(2)

The open-loop transfer function of the temperature control system is:

$$G_o(s) = K \times G_{\text{TEC}}(s) \times H_{\text{TEC}}(s) \times H_{\text{NTC}}(s)$$

(3)
4.2 NTC temperature measurement equivalent mathematical model
The transfer function of the thermistor temperature change to the ambient temperature change:

\[ H_{TH}(s) = \frac{1}{\tau_1 s + 1} \] (4)

In the formula, \( \tau_1 = C/H \), \( C \) is the thermal capacity of the thermistor; \( H \) is the thermal dissipation coefficient of the thermistor [3].

4.3 Equivalent mathematical model of TEC refrigeration
The transfer function of TEC temperature change and TEC voltage change:

\[ H_{TH}(s) = \frac{K}{\tau_2 s + 1} \] (5)

In the formula:

\[ K = \frac{K_u H_A}{H_A}, \tau_2 = \frac{C}{H_A}, \]
\( K_u = \frac{\Delta Q}{\Delta U} \) is the heat generated by the TEC temperature control surface per unit time, \( U \) is the voltage across the TEC, \( H \) is the heat transfer coefficient, \( A \) is the TEC heat transfer area, and \( C \) is the TEC heating coefficient [3].

4.4 Equivalent mathematical model of type III compensation network
The type III compensation network is shown in Fig. 3. Its transfer function has two zero frequencies, two pole frequencies, and an initial pole frequency:

The initial pole frequency is:

\[ F_{p0} = 1/(2\pi R_{13}C_{11}) \] (6)

The zero frequencies are:

\[ F_{z1} = \frac{1}{2\pi R_{13}C_0} \] (7)

\[ F_{z2} = \frac{1}{2\pi C_{10}(R_{14}+R_{15})} \approx \frac{1}{2\pi C_{10}R_{15}} \] (8)

The pole frequencies are:

\[ F_{p1} = \frac{1}{2\pi R_{13}C_{10}} \] (9)

\[ F_{p2} = 1/(2\pi \frac{R_{13}C_{11}}{C_0+C_{11}}) \approx \frac{1}{2\pi R_{13}C_{11}} \] (10)

5. Experimental results

5.1 Parameter setting of type III error amplifier adjustment circuit
Optimizing the parameters of type III compensation network can improve the stability of the temperature control system and achieve the purpose of optimal control. According to the NTC/TEC model, NTC/TEC can be described as a two-pole system. To avoid the phase lag introduced by the pole frequency resulting in the phase margin of the temperature control system is less than \( \pi/8 \), the two zero frequencies of the type III compensation network are used to compensate the phase delay caused by the TEC/NTC pole frequency, so that the two pole frequencies of the network can be far away from the imaginary axis, the influence of redundant pole frequency on the stability of the system can be minimized, and the relative stability of the system can be improved.

The optimization method is: first, we set the first zero frequency of the compensation network not to exceed 8 times the TEC pole frequency and set the second zero frequency of the compensation network to be lower than 1/3 of the shear frequency, so that the system has at least a phase margin of \( \pi/8 \) the amount. Then we set the corresponding open-loop gain at the cut frequency to -4dB. Finally, the shear frequency of the first pole frequency of the compensation network is set to be more than 5 times, and the second pole frequency of the compensation network is more than twice the first pole frequency to reduce the influence of the network pole frequency on the stability of the system.

Previous research [2] gives that the TEC pole frequency is around 0.02 Hz, the thermistor pole frequency is around 1 Hz, and the shear frequency \( F_c \) is around 1.5 Hz:

\[ F_{z1} = \frac{1}{2\pi R_{13}C_0} \] (11)
Based on formulas (11)~(15), where $C_9=10 \, \mu F$, $A=-4 \, dB$, $F_{z1}=0.16 \, Hz$, $F_{z2}=0.3 \, Hz$, $F_{p1}=15 \, Hz$, $F_{p2}=30 \, Hz$, we can get $R_{13}=99.47 \, k\Omega$, $C_{10}=0.58 \, \mu F$, $R_{15}=1.1 \, M\Omega$, $R_{14}=22 \, k\Omega$, $C_{11}=0.047 \, \mu F$, the final selected device parameters are: $C_9=10 \, \mu F$, $C_{10}=0.47 \, \mu F$, $C_{11}=0.047 \, \mu F$, $R_{13}=100 \, k\Omega$, $R_{14}=20 \, k\Omega$, $R_{15}=1 \, M\Omega$.

After the parameters of the type III compensation network are selected, the temperature resistance is set to 5 k$\Omega$ at an ambient temperature of 25 $^\circ$C, that is, the set temperature is about 43.5 $^\circ$C for temperature control testing. The long-term temperature change of TEC with time is shown in Fig. 8, and the system has temperature drift. The main reason is that the heating coefficient and thermal conductivity of different types of TEC are different; the heat capacity and heat dissipation coefficient of different types of thermistors are different, so that the TEC pole frequency, thermistor pole frequency and shear frequency are all different. When $C_{10}=0.47 \, \mu F$, $F_c=2.2 \, Hz$, that is, the shear frequency $F_c$ in the actual temperature control system should be less than 2.2 Hz.

![Figure 8 TEC temperature variation curve with time when the shear frequency is 2.2 Hz](image)

Set the cutting frequency to $F_c=1.56 \, Hz$, when the calculated parameters: $C_9=10 \, \mu F$, $C_{10}=0.68 \, \mu F$, $C_{11}=0.047 \, \mu F$, $R_{13}=100 \, k\Omega$, $R_{14}=20 \, k\Omega$, $R_{15}=1 \, M\Omega$, the change of TEC long-term temperature with time is shown in Fig. 9. There is no temperature drift in the system, which meets the application requirements of temperature control circuits. Here, Fig. 8 and Fig. 9 both control the temperature from room temperature, but since the temperature drift is on the order of mK, Fig. 9 intercepts the temperature change curve with time when the temperature is stable.
5.2 Analysis of temperature control performance results of temperature control circuit
Performance tests was conducted after adjusting the thermal conductivity, thermal shielding, and TEC control parameters of the temperature control circuit. Fig. 10 shows the measured temperature with a set temperature of 25 ℃ under different ambient temperatures. When the set temperature remains unchanged, the ambient temperature has a linear relationship with the measured temperature of the TEC. When the ambient temperature increases by 5 ℃, the TEC increases by about 0.06 ℃, and the temperature control gain is about 80. The curve of TEC temperature control accuracy versus ambient temperature is shown in Fig. 11. When the ambient temperature is close to the set temperature, the temperature control accuracy can be reduced to the lowest value. The cooling efficiency of the semiconductor refrigerator decreases as the temperature difference \( \Delta T \) between the hot and cold ends increases, resulting in a decrease in the temperature control accuracy as the temperature difference between the ambient temperature and the set temperature increases [8]. When the ambient temperature is 25 ℃, the highest temperature control accuracy is about 0.3 mK; when the ambient temperature is 40 ℃, the worst temperature control accuracy is about 1.5 mK. Fig. 12 shows the long-term temperature change curve of TEC when the ambient temperature is 25 ℃.
6. Conclusion
In this paper, the SLD high-precision temperature control circuit is designed based on the type III compensation network using the Max1978 chip. The temperature deviation experiment is carried out in the environment temperature of 5~40 °C, the temperature control gain is measured to be about 80, and the temperature control accuracy of TEC under different environmental temperatures is detected. The maximum temperature control accuracy is about 0.3 mK when the environment temperature is 25 °C. The temperature control accuracy is the lowest when the temperature is 40 °C, which is about 1.5 mK.

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