An improved temperature compensation circuit for SLD light source of fiber-optic gyroscope

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Abstract. The super luminescent diode light source is commonly used in Fiber-optic gyroscope. The wavelength temperature stability is one of its key parameters. In this work, simulation model of temperature field of the SLD light source is established, and the temperature distribution of SLD internal structure is simulated and researched. A temperature compensation scheme is designed according to the simulation result and experiment is done to confirm the specific parameter of compensation circuit. Then the designed compensation scheme is used in temperature control circuit of SLD, and the performance of compensated SLD light source is tested. An improvement of 62% is demonstrated compared with uncompensated SLD.

1. Introduction

Fiber-optic gyroscope (FOG) is a kind of angular velocity sensor based on the Signac effect. It has shown great advantages such as small volume, light weight, wide range of accuracy, and no need for moving parts [1], and has been extensively applied in applications such as aviation, spaceflight, and navigation [2, 3].

There are two kinds of light sources commonly used in recent FOG technology, the super luminescent diode (SLD) and the amplified spontaneous emission (ASE). The SLD light source shows various advantages such as small size, low cost and broad spectrum [4], and is commonly used in the low and medium precision FOG. Compared with SLD light source, the ASE light source shows better wavelength temperature stability [5, 6, 7], which makes it suitable for applications such as high precision FOG [8, 9].

Recently, as more and more attentions has been paid to space application of FOG, it becomes highly demanded to improve source system of the spatial FOG [10]. Since the light power and wave length of ASE light source will be unstable in space due to the cosmic radiation [11, 12], SLD light source is a common scheme for special FOG system. While the wavelength temperature stability of the sources remains problem to be solved for high precision FOG [13].

In this work, the cause factor of wavelength temperature instability in SLD is analysed and a simulation model of temperature field is established. Based on the simulation result, an improved SLD temperature compensation circuit has been proposed and demonstrated in experiment. An improvement of 62% is demonstrated.
2. Analysis of traditional temperature control scheme of SLD

In the construction of SLD light source, negative temperature coefficient (NTC) thermistor and thermoelectric cooler (TEC) are used to achieve temperature feedback control of tube core. Fig. 1 shows the typical SLD structure [14]. TEC works as semiconductor cooler and nickel heat sink is put on its upper surface for heat conduction. The tube core is soldered on the heat sink and the NTC thermistor is soldered closed to it. The tube core behaves like a heat source in thermal analysis, and the thermistor beside is a heat sensor of tube core.

![Figure 1. The typical construction of SLD light source](image)

Special temperature control circuit is designed to keep SLD in a certain temperature. Fig. 2 shows a traditional temperature control circuit of SLD light source [15]. $R_0, R_1, R_2$ are precision resistance, and the value of $R_1$ is equal to $2R_2$. $R_T$ represents the NTC thermistor in SLD. $U_1$ is instrument op-amp which produces control signal of TEC. The feedback circuit works so that the value of $R_T$ is controlled to be equal to $R_0$, so that the working temperature of SLD is controlled by the value of $R_T$. In this way, the setting temperature of SLD keeps stable during working.

![Figure 2. Traditional temperature control circuit of SLD light source](image)

While the structure shown above shows great disadvantages, it still has drawback. When the circuit works, it is the temperature of NTC thermistor that has been controlled instead of tube core temperature. Since there is a small spatial distance from NTC thermistor to tube core, so there is a slight temperature difference between them. Although temperature of thermistor has been seriously controlled, slight temperature fluctuation still exists in tube core when external temperature changes. As the temperature characteristic of tube core is about $500 \text{ ppm/} ^\circ \text{C}$, the slight fluctuation in tube core leads to wavelength instability of SLD light source. In fiber-optic gyroscope, the mean wavelength of light source, $\lambda$, is related to the scale factor of FOG output, $K_x$, which can be described as
\[ K_s = \frac{\Omega}{\Phi_S} = \frac{\lambda \cdot c}{8\pi S} \]  

(1)

Where \( \Phi_S \) is the Sagnac phase shift, \( \Omega \) is the angular velocity of rotation, \( c \) is light velocity and \( S \) is the total area of the closed light path. The mean wavelength of light source is proportional to the scale factor. If the mean wavelength is unstable, then the FOG output is unstable too. In such situations, the wavelength temperature instability problem greatly restricts SLD’s applications in high precision FOG.

3. Temperature characteristic of SLD with traditional control scheme

The temperature distribution of SLD is researched in order to solve the temperature instability problem discussed above. Simulation model of temperature field is established according to the actual working status of SLD light source.

Heat has three transfer ways including radiation, convection and conduction. In SLD device, heat exchange happens in a small close space, so the heat mainly transfers through metal structures of SLD. This transfer way is called heat conduction. Heat conduction equation describes the temperature distribution inside solid structure as below:

\[
\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \kappa_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \kappa_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \kappa_z \frac{\partial T}{\partial z} \right) + \rho Q
\]

(2)

Where \( T \) denotes temperature distribution, \( t \) denotes the time, \( \rho \) denotes the density, \( \kappa_x \), \( \kappa_y \), \( \kappa_z \) respectively denote heat conductivity coefficient through \( x \), \( y \), \( z \) direction, and \( Q \) denotes heat source inside solid structure. As the SLD works in steady state, transient response of Eq(2) can be ignored, then neat conduction equation of steady state can be described as.

\[
\frac{\partial}{\partial x} \left( \kappa_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \kappa_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \kappa_z \frac{\partial T}{\partial z} \right) + \rho Q = 0
\]

(3)

The SLD works in a good heat dissipation condition, so the heat dissipation surfaces can keep the same temperature as outside environment. On purpose of simplify the boundary conditions during temperature field simulation, the convective boundary, radiation boundary and conduction boundary can all be replaced by a unified temperature boundary, which can be described as.

\[ T(M) \big|_{M \in S_i} = T_e \]  

(4)

Where \( S_i \) denotes the heat dissipation surfaces of SLD structure, and \( T_e \) denotes the environment temperature.

Then the heat simulation is carried out after temperature and structure model has been established. During the simulation, the temperature of NTC thermistor, \( T_{\text{NTC}} \) keeps \( 25^\circ C \) within the interaction of tube core and TEC, and the temperature distribution has been calculated when environment temperature changes from \(-40^\circ C \) to \( 70^\circ C \). Fig.3 shows the structure model and an example of thermal field distribution of SLD light source. In this example, the environment temperature was \( 10^\circ C \), and NTC thermistor temperature was controlled in \( 25^\circ C \). The tube core temperature was calculated to be \( 28.7^\circ C \).
Figure 3. An example of simulation result of the temperature distribution inside SLD. The environment temperature is $10^\circ C$, and NTC thermistor temperature is controlled in $25^\circ C$. The shell and optical structure has been hidden in the graph.

From the result of thermal field distribution, a temperature difference of about $4^\circ C$ can be demonstrated between the tube core and NTC thermistor. And this temperature difference can be influenced by the environment temperature. As a result, although the temperature of NTC thermistor, $T_{th}$ is controlled to keep on $25^\circ C$, the tube core temperature, $T_{core}$, still changes with the environment temperature, $T_e$. The simulation result about the relationship of $T_{core}$, $T_{th}$ and $T_e$ is shown in Fig.4.

Figure 4. The simulation result as $T_{th}$ is controlled to $25^\circ C$

According to simulation result, there is a linear relationship between $T_{core}$ and $T_e$. Experiment about the wavelength temperature instability has been done to demonstrate the simulation result. The mean wavelength of a SLD product has been measured by optical spectrum analyser with environment temperature changing from $-40^\circ C$ to $70^\circ C$. The test result is shown in Fig.5. The mean wavelength has
changed about 300ppm in a linear fashion. Since the mean wavelength of SLD is almost linear to the temperature of the tube core, a conclusion can be gotten that tube core temperature is linear to environment temperature which is also demonstrated by simulation result mentioned above.

![Figure 5. Test result of wavelength temperature instability without compensation](image)

4. Temperature compensation scheme of SLD

In traditional temperature control scheme, the temperature of NTC thermistor keeps in a fixed value. This leads the tube core temperature to change linearly with environment temperature. In order to keep the tube core temperature stable, the temperature of NTC thermistor should also change with the environment temperature. Follow this approach, a temperature compensation scheme can be developed.

Another simulation has been taken to study the change of the thermistor temperature when tube core temperature is fixed. The temperature of tube core, $T_{\text{core}}$ keeps on $25^\circ\text{C}$ and the environment temperature, $T_e$ changes from $-40^\circ\text{C}$ to $70^\circ\text{C}$. The simulation result is shown in Fig.6. In order to keep the tube core temperature stable in $25^\circ\text{C}$, the temperature of NTC thermistor, $T_{th}$ should change from $21.5^\circ\text{C}$ to $21.1^\circ\text{C}$ linearly.
Figure 6. The simulation result when $T_{core}$ is controlled to keep on 25°C.

Experiment has been designed according to the simulation result in order to find the appropriate compensation resistance. Fig.7 shows the experiment scheme. An 300Ω adjustable resistor, $R_{adj}$, was cascaded to $R_0$ on the basis of circuit shown in Fig.2. The control circuit and SLD light source were placed in a temperature control box, but $R_{adj}$ was put outside so that its resistance can be adjusted by experimenter. As circuit works, the value of NTC thermistor inside SLD, $R_T$, can be determined by

$$R_T = R_{adj} + R_0$$

(5)

So the controlled temperature of NTC thermistor can be adjusted by $R_{adj}$. The output of SLD light source was connected to an optical spectrum analyzer to monitor the mean wavelength of SLD.

Figure 7. Experiment scheme to test out the appropriate compensation resistance.

The temperature of the box, $T_e$ changes from -40°C to 70°C in steps of 10°C. The mean wavelength at -40°C was recorded as the original value. At each temperature spot, $R_{adj}$ was slightly adjusted until
the mean wavelength reached the original value. The values of $R_{adj}$ with different temperature were recorded and the relationship curve between $R_{adj}$ and $T_e$ can be drawn as Fig.8.

![Graph showing the relationship between $R_{adj}$ and $T_e$.](image)

**Figure 8.** Test result of the compensation resistance

As shown in Fig.8, there is a linear relation between the resistance and the temperature, which means that a compensation resistor can be added to traditional SLD control circuit in order to get better wavelength temperature stability.

A positive temperature coefficient (PTC) thermistor, $R_{PTC}$ was chosen as the compensation resistor according to Fig.8. Its resistance was $450\Omega$ at $25^\circ C$, and changed from $330\Omega$ to $530\Omega$ linearly as temperature raised from $-40^\circ C$ to $70^\circ C$. The compensated SLD control circuit was shown in Fig.9. $R_1$, $R_2$ was $10\kOmega$ high precision resistor. $R_p$ Was $9.8\kOmega$ high precision resistor. $R_T$ Was the NTC thermistor inside SLD. As the circuit working, $R_T$ can be determined by

$$R_T = R_{PTC} + R_p$$

(6)

![Circuit diagram showing the compensated SLD temperature control circuit.](image)

**Figure 9.** The compensated SLD temperature control circuit
The PTC thermistor, $R_{PTC}$, provided temperature compensation for $R_T$. This compensation value made the temperature of NTC thermistor, $T_{th}$ adjust slightly in the similar way as Fig.6. In this way, temperature of tube core, $T_{core}$ became more stable when environment temperature changed, so wavelength temperature stability of SLD has been improved.

5. Temperature stability test of temperature compensated SLD

The temperature compensation scheme above provides a method to improve wavelength temperature stability of SLD light source. Temperature stability test has been done to verify the compensation effect of designed circuit. The SLD light source was controlled and driven by compensated circuit shown in Fig.9, and its wavelength temperature stability has been tested. Fig.10 shows the test result. The mean wavelength drift value was about 115ppm when environment changed from $-40^\circ C$ to $70^\circ C$. Compared with the temperature stability of uncompensated SLD light source in Fig.5, evident improvement of 62% was demonstrated.

![Figure 10. Test result of wavelength temperature stability after compensation](image-url)

While as shown in Figure 10, small wavelength drift still exists after the SLD has been compensated. This is because this compensation scheme is not perfect and can be further improved. Firstly, the non-ideality of the PTC compensation thermistor confines the compensation effect. Secondly, operating environment of SLD provides random influence such as circuit noise and mechanical vibration. Thirdly, the test accuracy of optical spectrum analyzer is 0.05nm, which may amplify the rise and fall in test value. What is more, this compensation only aims at steady state of SLD, and the compensation effect can be further improved if transient characteristic of SLD has been studied and compensated.

6. Conclusion

The wavelength temperature stability of SLD light source is an important problem in the application of high precision FOG. Simulation and experiment has been done to study the temperature distribution of SLD internal structure, and a temperature compensation scheme has been designed. In this temperature compensation scheme, a specific compensation thermistor has been used to provide temperature compensation in the TEC control circuit of SLD. The compensation thermistor features with a certain resistance-temperature curve and can be used to change the setting temperature of SLD with environment temperature. In this way, the temperature of tube core can be more stable. This temperature compensation circuit has been applied and tested, and a wavelength temperature stability improvement of 62% was demonstrated in the compensated SLD light source.
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