Research on the mean-wavelength drift mechanism of SLD light source in FOG

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Abstract. The SLD light source is widely used in fiber optical gyroscope (FOG), and its mean-wavelength stability directly influenced the scale factor stability of FOG. The research on mean-wavelength drift of light source can improve the scale factor of FOG and, consequently, suppress the angle error of inertial navigation system. In this work, the luminous mechanism of semiconductor light source was considered and influence factors of SLD spectrum were analyzed. Based on simulation and experiment, the main causes of SLD mean-wavelength drift has been indicated, including the temperature drift of drive circuit and the temperature control error caused by position of thermistor. This research has made an instructive contribution to the development of FOG light source stability.

1. Introduction

Light source is one of the key components of fiber optical gyroscope. The performance of FOG is directly related with the output quality of its light source[1-3]. From the Sagnac effect, the scale factor, $K$, of FOG can be described as

$$K = \frac{8\pi S}{\lambda c} \propto \frac{1}{\lambda}$$

(1)

Where $\lambda$ is the mean wavelength, $c$ is light velocity and $S$ is the total area of the closed light path. So the mean wavelength error, $\Delta\lambda$, is proportional to the scale factor error, $\Delta K$, which can be described as

$$\Delta K = \frac{8\pi S}{c\lambda^2} \Delta\lambda$$

(2)

In this way, the mean wavelength stability of light source directly determines the scaling factor stability of FOG [4-5].

The superluminescent diode, SLD, light source is commonly used in Fiber-optic gyroscope. The research on its mean wavelength drift can be meaningful for the suppression of FOG scale factor error. Jianling Yin from Ordnance Engineering College has studied the effect of themistor resistance position...
in SLD for its temperature control parameters[6]. Shigang Yin from Zhejiang University has designed digital FOG driver with output accuracy of 0.03mA, and consequently realized the mean wavelength stability of 90 ppm[7]. Xi Zhang from Beijing University of Aeronautics and Astronautics has used optical feedback scheme to control the temperature of SLD and reached a precision of 0.1°C [8]. These achievements has partly improved the mean wavelength stability of SLD. But there is a lack of research on drift mechanism of SLD mean wavelength, especially during its application in FOG.

In this work, the spectral characteristic of SLD was studied and its influence factors was analyzed. Combine with simulation and experiment, the drift mechanism of SLD mean wavelength was researched. Consequently, this study indicated the sources of drive current drift and temperature control error in SLD control system, which makes a contribution to the suppression of SLD mean wavelength and improves the stability of FOG scale factor.

2. Simulation Analysis of the SLD Emission Spectrum

The quantum-well SLD is a widely used kind of superluminescent diode light source. It exhibits high stability, low threshold current and excellent luminous efficiency[9]. Considering the carrier relaxation effect, the active region gain spectrum of quantum-well SLD can be described as [10-11]

\[
g_{\omega}(\omega) = n \frac{B_{\omega}}{c} \frac{m_{r}}{d^{2} \pi^{2} R^{2}} \int_{E_{c}}^{E_{v}} \frac{\frac{h\gamma}{2}(f_{c} - f_{r})}{(E - \hbar \omega)^{2} + (\frac{h\gamma}{2})^{2}} \, dE
\]

Where \( n \) is the refractive index, \( d \) is the active region thickness, \( E_{c} \) is the bandgap, \( m_{r} \) is the effective mass of vibrator, \( \gamma \) is damping coefficient of its complex polarization model, \( B_{\omega} \) is Einstein coefficient. \( f_{c} \) and \( f_{r} \) are determined by

\[
f_{c} = \frac{1}{e^{\frac{i\omega}{\gamma}} + 1}
\]

\[
f_{r} = \frac{1}{e^{\frac{i\omega}{\gamma}} + 1}
\]

Where \( m_{e} \) is the electron effective mass, \( m_{h} \) is the hole effective mass, \( E_{c} \) is the bottom of conduction band, \( E_{v} \) is the top of valence band, \( F_{c} \) and \( F_{r} \) are splitted Fermi levels.

The spectral characteristic of a typical kind of quantum-well SLD has been studied. Its active region material is InGaAsP with 0.95eV band gap energy. And the central wavelength is 1310nm. Numerical simulation of InGaAsP heterojunction indicated the relationship between injected carrier density, \( N \), and its stimulated emission spectrum, which is shown in Figure 1.
And the relationship between core temperature and stimulated emission spectrum can be shown as Figure 2.

From the numerical simulation result, Conclusions can be drawn that SLD stimulated emission spectrum drifts towards higher frequency when the injected carrier density becomes higher, and drifts towards lower frequency when its core has higher temperature.

3. Spectral Character of SLD Light Source
The stimulate emission characteristic of SLD light source is influenced by the core temperature and injected carrier density. In this section, experiments has been made to analyze the temperature and current characteristics of SLD emission spectrum.

3.1. The Temperature Characteristic of SLD Emission Spectrum
The output spectrum of SLD has been tested in different temperature. The driven current kept 100mA during the test, while the core temperature rose up from 15°C to 45°C. The output mean wavelength and spectrum width has been measured during the experiment. And the test results are listed in Table 1. It shows that the mean wavelength becomes shorter when temperature declines, which is also demonstrated by simulation result mentioned above.
Table 1. Test results of SLD mean wavelength and spectrum width in different temperature

| Temperature/°C | 15   | 20   | 25   | 30   | 35   | 40   | 45   |
|----------------|------|------|------|------|------|------|------|
| Mean wavelength/nm | 1300.85 | 1303.34 | 1306.13 | 1309.15 | 1312.30 | 1315.62 | 1319.03 |
| Spectrum width /nm   | 42.76  | 43.20  | 43.62  | 44.02  | 44.40  | 44.76  | 45.13  |

When the temperature changes, the varying tendency of mean wavelength and spectrum width are in a linear fashion as shown in Figure 3.

![Figure 3](a) ![Figure 3](b)

Figure 3. Test result of output spectrum in different core temperature. And (a) shows the relationship between mean wavelength and temperature. (b) shows the relationship between spectrum width and temperature.

From the measurement result, the wavelength-temperature drift coefficient of tested SLD is 0.606nm/°C, which figures out to be 462ppm/°C. And the bandwidth-temperature drift coefficient of tested SLD is 0.078nm/°C, which figures out to be 0.17%/°C.

3.2. The Current Characteristic of SLD Emission Spectrum

The output spectrum of SLD has also been tested in different driving current. And during the experiment, core temperature remained 25°C, while the driving current rose up from 70mA to 130mA. The output mean wavelength and spectrum width has been measured during the experiment. And the test results are listed in Table 1. It indicates that the mean wavelength becomes longer when driving current declines, which is also demonstrated by simulation result mentioned above.

Table 2. Test results of SLD mean wavelength and spectrum width in different driving current

| Driving current/mA | 70   | 80   | 90   | 100  | 110  | 120  | 130  |
|--------------------|------|------|------|------|------|------|------|
| Mean wavelength/nm | 1317.43 | 1315.21 | 1313.32 | 1311.77 | 1310.49 | 1309.46 | 1308.63 |
| Spectrum width /nm | 39.70  | 40.97  | 42.05  | 42.96  | 43.85  | 44.68  | 45.56  |

When the driving current changes, the varying tendency of mean wavelength and spectrum width are in a linear fashion as shown in Figure 4.
Figure 4. Test result of output spectrum in different driving current. And (a) shows the relationship between mean wavelength and current. (b) shows the relationship between spectrum width and current.

From the measurement result, the wavelength-current drift coefficient of tested SLD is -0.147nm/mA, which figures out to be 112ppm/mA. And the bandwidth-current drift coefficient of tested SLD is 0.098nm/mA, which figures out to be 0.22%/mA.

4. Mean Wavelength Drift of SLD in the Application of FOG

4.1. Mean Wavelength Drift Caused By Driving Current

For traditional current drive circuit of SLD, current temperature drift comes from three factors, including temperature drift of voltage reference, temperature drift of power circuit, and temperature drift of sampling resistor.

The temperature drift coefficient of typical voltage reference, \( \kappa_{\text{ref}} \), can be 10ppm/°C. The voltage reference value is set to be 1.25V. And the temperature drift coefficient of offset voltage, \( \frac{dV_{\text{OS}}}{dT} \), in typical power amplifier can be \( \pm 1.3 \mu V/\degree C \). Then the temperature drift coefficient caused by power amplifier, \( \kappa_{\text{OSV}} \), can be described as

\[
\kappa_{\text{OSV}} = \frac{dV_{\text{OS}}}{dT} \cdot \frac{1}{V_{\text{ref}}} = 1.04 \text{ppm}/^\circ C
\]

The temperature drift coefficient of typical sampling resistor, \( \kappa_{\text{R}} \), can be \( \pm 50 \text{ppm}/^\circ C \). The total temperature drift, \( \kappa_{\text{tot}} \), is the combined effect of all the electronic components in the circuit, as a result, the theoretical maximum value of \( \kappa_{\text{tot}} \) can be described as

\[
\kappa_{\text{tot}} = \left| \kappa_{\text{ref}} \right| + \left| \kappa_{\text{OSV}} \right| + \left| \kappa_{\text{R}} \right| \approx 61 \text{ppm}/^\circ C
\]

The measured value of \( \kappa_{\text{tot}} \) tends to be less than \( \kappa_{\text{tot}} \). And the measurement result of temperature drift in traditional current drive circuit is shown in Figure 5.
4.2. Mean Wavelength Drift Caused By Temperature Control Error

Temperature control error can exist in the SLD temperature control circuit under the condition of full temperature. This kind of temperature error will also lead to mean wavelength drift. The direct cause of this temperature control error is the position difference between the thermistor and the tube core in the SLD structure. The heat model has been established based on SLD structure as shown in Figure 6(a). During the simulation, the temperature of NTC thermistor, $T_{NTC}$, keeps 25°C within the interaction of tube core and TEC. And the temperature distribution has been calculated when environment temperature changes from -40°C to 60°C. Although the temperature of NTC thermistor, $T_{th}$, is controlled to keep on 25°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 Figure 6(b).

According to simulation result, the core temperature rises linearly from 28.5°C to 28.8°C while environment temperature changes from -40°C to 60°C. And the full-temperature variation of core temperature, $\Delta T_{th}$, is 0.3°C.
Experiment has been made to verify the error model of SLD temperature control. As shown in Figure 7(a), traditional temperature control circuit has been used to control SLD, so that the temperature of NTC thermistor can be controlled at 25°C. And the mean wavelength has been tested while environment temperature changes from -40°C to 60°C. During the experiment, the current driving circuit and temperature control circuit has been put outside the temperature control box. In this way, the temperature drift of circuit will not affect the accuracy of test results.

According to the test result, the test value of full-temperature variation of SLD mean wavelength is 148ppm. As mentioned in section 3.1, the wavelength-temperature drift coefficient of tested SLD is 462ppm/°C, then we can draw a conclusion that the full-temperature variation of SLD core temperature is measured to be 0.32°C. This test result is close to 0.32°C, as the simulation result stated above. The SLD temperature drift model and mechanism have been verified.

In summary, there are two main reasons for the mean wavelength temperature drift of SLD light source: one is the temperature drift of driving current, the other is the drift of core temperature caused by temperature control error.

5. Conclusion
The essence of the stability problem of the SLD mean wavelength is the change of spectral characteristics in semiconductor light source, which caused by the change of carrier concentration and core temperature. In the control circuit of FOG light source, the main influence factors of mean wavelength are current drift of driving circuit and the control error of temperature control circuit. When the environment temperature changes, the output current of the driving circuit drifts with the temperature, and the position difference between the thermistor and the core will lead to temperature control error. When environment temperature changes from -40°C to 60°C, there is a current drift of about 0.13mA in current driving circuit of SLD, which will result in a mean wavelength drift of about 15ppm. The mean wavelength drift caused by the temperature control error is measured to be 148 ppm. This experimental result is in good agreement with the theoretical simulation. Therefore, it can be concluded that in order to suppress the average wavelength temperature drift of SLD light source, it is necessary to design a current driving circuit with high temperature stability, and adopt a specific scheme to reduce the temperature control error caused by the position difference of thermistor.

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