第 42 卷第 3 期
2023 年 6 月

红 外 与 毫 米 波 学 报
J. Infrared Millim. Waves

Vol. 42, No. 3
June, 2023

**文章编号**：1001-9014（2023）03-0377-06

**DOI**：10. 11972/j. issn. 1001-9014. 2023. 03. 013

# A method to evaluate the thermal resistance of a laser by wavelength hysteresis

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**Abstract**: Packaging is one of the key technologies of optoelectronic devices. It also determines the performance of the packaged device. In the article, a method based on wavelength hysteresis is proposed to evaluate the thermal resistance of the laser at ambient temperatures from 298 K to 10 K. The thermal resistance is characterized by calculating the value of wavelength hysteresis during the cooling and heating process. This method solves the problem that the heat dissipation performance of the laser cannot be evaluated at low temperatures. This is of great significance to the optical interconnection at low temperatures. It also provides a reference for the package design of lasers in a low-temperature environment.

**Key words**: thermal resistance, wavelength hysteresis, low temperature, semiconductor laser

# 波长滞后法评估激光器的热阻

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**摘要**：封装是光电子器件的关键技术之一。同时，器件的封装还影响器件的性能。文章提出了一种基于波长滞后的方法来评估激光器在298 K至10 K环境温度范围内的热阻。通过计算降温和升温过程中波长滞后的程度来表征热阻大小。该方法解决了低温环境中无法评估激光器散热性能的问题。这对低温光互连具有重要意义，也为低温环境中激光器的封装设计提供了参考。

**关　键　词**：热阻；波长滞后；低温；半导体激光器

**中图分类号**：O514.2；O433；O4-34；O551.1；O47　　　　**文献标识码**：A

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**Received date**: 2022-10-29, **revised date**: 2023-01-09　　　　**收稿日期**：2022-10-29，**修回日期**：2023-01-09

**Foundation items**: Projects were supported by the National Natural Science Foundation of China (61875252, 92165202), the Strategic Priority Research Program (A) of Chinese Academy of Sciences (XDA18040300).

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## Introduction

Semiconductor technology is changing with each passing day. The technology of the package also distinguishes between microelectronic packaging and optoelectronic packaging[1]. In the process of optoelectronic packaging, many elements must be considered, such as optical coupling efficiency, impedance matching and the characteristics of the thermal[2]. Especially in the packaging process of high-speed modulated lasers, the crosstalk for electrical and optical signals should be avoided; besides, the thermal properties should be focused. The heat generation of the semiconductor lasers is severe with a high current injection. The rise of the temperature in the active region will bring a series of effects, including the increase of threshold current, the decrease of electro-optic conversion efficiency, and the shift of lasing wavelength[3]. These influences seriously limit the performance and application of semiconductor lasers.

The thermal resistance represents the efficiency of heat transfer between media. The package thermal resistance of the laser is used to evaluate the heat dissipation of the laser. At present, the main packaging forms of high-speed semiconductor lasers are Transistor-Outline (TO-Can) and Butterfly[2]. Researchers focus on improving device performance by improving packaging. For example, in 2010, NTT of Japan reported a Distributed Feed Back (DFB) laser, which realized 40 Gb/s long-distance transmission using special transmission lines and series resistors[4]. The technology of packaging restricts the performance and life of semiconductor optoelectronic devices. The Catalytic Optical Mirror Damage (COMD) and thermal rollover greatly impact on the output power of semiconductor lasers. Thus, the thermal effect of packaging is an urgent problem to be solved.

The characteristics of packaging thermal are important for lasers operating at low temperatures. Generally, small semiconductor lasers have low heat output and fast heat conduction rates at room temperature. More attention is paid to the impact of packaging on performance[2], rather than the thermal effect of packaging. Even if some lasers need to be used at the ambient temperature of 77 K, the longer waiting time can ensure temperature stability[5]. However, for semiconductor lasers, especially devices with high output power and severe heating, the lower the ambient temperature, the more significant the impact of thermal shock caused by injecting current. The semiconductor lasers with packaging can work at 10 K[6-7]. Compared with the style of a direct chip without a package[8], its performance is much lower. In the applications of superconducting computers[9-10], device packaging is essential. In the superconducting environment, different thermal expansion coefficients of materials increase the cost of package designs. As the most heat-generating device in the vacuum chamber, the directly modulated laser interferes with other types of equipment and increases the pressure of the refrigerator.

In this paper, we propose a method based on wavelength hysteresis to evaluate the thermal resistance of the semiconductor laser operating in a low-temperature environment. The thermal resistance is difficult to be measured directly. Besides, it cannot be measured in the vacuum chamber. Currently, popular measurement methods and commercial measurement systems face significant difficulties in measuring complex cryogenic systems. This problem is generally solved by indirect methods. It is found that some parameters of the laser will change regularly varying with ambient temperatures. In this way, the thermal resistance of the laser at different ambient temperatures can be characterized through wavelength shifts. This is of great significance to the optical interconnection at low temperatures.

## 1 Theoretical calculation

The measurement of thermal resistance is very important for high-power lasers. The high dissipation power will lead to a significant reduction in quantum yield or even damage to equipment[11]. Here are two classic ways to solve the problem.

It is a common method to use a thermal model based on the thermoelectric analogy principle[12]. It also helps to determine the temperature distribution in the device structure. According to it, the process of the heat flow could be compared with the RC link in the electrical process. The current corresponds to the heat flow. The voltage is regarded as the temperature. The resistance and capacitance are treated as the thermal resistance and heat capacity, respectively. And the constant of the RC is considered the constant of thermal time. In this way, the thermal resistance is determined by Foster's network and Cauer's network. Although the parameters of each network are different, Forster's parameters can be converted to Cauer's network. The conversion process is described in the JESD51-14 standard[13]. There are also some improvements, such as a structure-function-based method, proposed in Ref. [8] and Ref. [9], to obtain the contribution of each element in the thermal model to the thermal resistance[14-15].

Transforming thermal resistance measurement into thermal curve analysis is another means of characterization[16]. Flick T used different pulses to drive the laser to obtain the changing parameters and then converted them into the wavelength curve changing with temperatures.

The method of thermal analogy is mature. Its disadvantage is that the modeling is tedious and complex. It is mainly used for high-power semiconductor lasers. It also takes a long time to evaluate the dependence of the thermal model on frequency. Nevertheless, this method is unsuitable for the directly modulated laser operated in variable temperatures. This is because the impedance of the directly modulated laser is related to the transmission rate. The measurement of the transmission rate depends on the output power. And the output power is influenced by the package. The package is also related to the temperature. The temperature is a function of time, which makes the device's impedance related to time. In a low-temperature environment, the refrigerator provides refrigerating capacity constantly. The mixed signal of modulation and bias drives the laser. However, it also brings a period of a thermal pulse. The heat conduction would take some time. The impedance of the laser will be disordered easily. The time required for data fitting cannot be obtained.

The spectral method is also not applicable to the ambient environment near 10 K. In Ref. [16], the injection current and duty cycle are changed to make the wavelength red shift first and then blue shift with reduced ambient temperature. The influence of junction temperature could be ignored in the unchanged thermal resistance. This method seems perfect above 0 ℃. Unfortunately, in the low-temperature environment, the change of material thermal expansion coefficient and thermal conductivity indeterminately makes this method undesirable. In addition, the cavity mode and gain spectrum will be mismatched[7], resulting in the inability to obtain the thermal equilibrium point.

We propose a wavelength hysteresis method to evaluate the heat transfer of the semiconductor laser package in a variable temperature environment.

$$R_{th} = \frac{L}{\kappa S} \quad , \quad (1)$$

where, $R_{th}$ is thermal resistance; $L$ is the geometric dimension of the material between the measuring points; $\kappa$ is the thermal conductivity; $S$ is the heat transfer area. Equation 1 is the basic definition of thermal resistance. However, it is usually difficult to calculate the thermal resistance of semiconductor lasers with the help of Equation 1. Equation 2[16] is more familiar:

$$R_{th} = \frac{T_j - T_{amb}}{P_{in} - P_{opt}} \quad , \quad (2)$$

where, $T_j$ is the junction temperature; $T_{amb}$ is the ambient temperature; $P_{in}$ is the input electrical power; $P_{opt}$ is the output optical power. For semiconductor lasers, the temperature of the junction is higher than the package. The junction temperature is difficult to be measured directly. Equation 1 describes the formation of thermal resistance. And Equation 2 describes the relationship between thermal resistance and junction temperature.

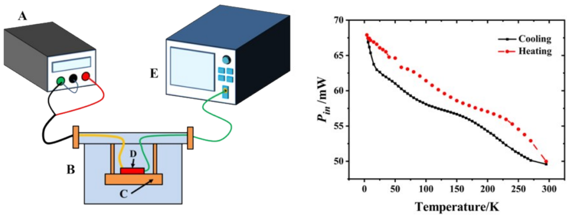
In the room temperature environment, the output power of the semiconductor laser is far less than the power consumption. $P_{in} \gg P_{opt}$. Therefore, Equation 2 can be simplified as:

$$R_{th} = \frac{T_j - T_{amb}}{P_{in}} \quad , \quad (3)$$

where, $P_{in} = I^2 R_s + I_{th} V_j$. $I$ is the injection current. $R_s$ is the impedance. $I_{th}$ is the threshold current. $V_j$ is the voltage of the junction. Equation 3 is the basis of most methods. These methods are based on the premise that the denominator is independent of temperature. It is inevitable at room temperature. In this way, the term of junction temperature can be eliminated by changing the measurement conditions, because the denominator is independent of temperature[16]. However, both the power consumption and the luminous power of the laser are temperature-dependent. This has been stated in the above section. This makes it impossible to directly cancel the junction temperature in the numerator ignoring the denominator after changing the test conditions. The change in material deformation and coupling efficiency cannot be ignored yet.

Generally speaking, the quantum efficiency of the laser will be improved in a low-temperature environment. In numerical value, the luminous power cannot catch up with the Direct Current (DC) power[6]. In this way, Equation 2 can still be changed to Equation 3.

In Equation 3, the two independent variables that will affect the thermal resistance are junction temperature $T_j$ caused by injection current and ambient temperature $T_{amb}$. When the injection current keeps constant, the junction temperature remains unchanged. Although the $P_{in}$ in the denominator is related to temperature, it does not contribute to the spectral shift when the injection current is fixed. Thus, the spectral shift is only related to the cavity deformation. In the process of cooling or heating, the cavity deformation is related to the ambient temperature. In brief, the shift of the spectrum is only related to the ambient temperature.



(a)　(b)

Fig. 1　(a) The wiring diagram. A: Direct Current Source; B: Low-temperature Vacuum Chamber; C: Temperature Control Platform; D: Laser; E: Fiber Optic Spectrometer, (b) the power dissipation $P_{in}$ changes with temperatures

图 1　(a)实验连线图,A:直流源;B:低温真空腔;C:温控台;D:激光器;E:光纤光谱仪,(b)功耗 $P_{in}$ 随温度的变化曲线

The evaluation system was built, including Direct Current Source, temperature-controlled vacuum chamber and Fiber Optic Spectrometer. Figure 1a shows the wiring diagram in the experiment. In the Low-temperature Vacuum Chamber, the Laser was tightly attached to the Temperature Control Platform. The special coaxial cable introduced the injection current into the low-temperature vacuum chamber. The thermometer was close to the temperature control platform to display the ambient temperature. The light was introduced into the fiber optic spectrometer through optical fiber. In the experiment, the laser operates in the linear region and the injection current remains unchanged. Record the corresponding spectrum with a fiber optic spectrometer when changing the ambient temperature. At the same time, record the *V-I* array of the laser at different ambient temperatures through a digital multimeter.

Figure 1(b) shows the change of electric power $P_{in}$ with temperatures during cooling and heating. The packaging form of the laser is the Transmitter Optical Subassembly (TOSA). The injected current is maintained at 20 mA.

During the cooling process, the slope is −4. 71 ×

$10^{-6}$ W/K in the range of 20 K to 4. 2 K, and the slope becomes $-3.06 \times 10^{-5}$ W/K in the range of 293 K to 20 K. The negative sign only indicates that the vacuum chamber is cooling. In the heating process, the curve changes linearly with temperature, the slope is $5.3 \times 10^{-6}$ W/K.

According to Equation 1, the parameter $\kappa$ changes with temperatures. Thus, in Equation 3, the right side of the equation is a function of temperature. Equation 3 can be described as Equation 4:

$$R_{th} = \frac{f_1(T)}{f_2(T)} \quad , \quad (4)$$

where, $f_1(T) = T_j - T_{amb}$, $f_2(T) = P_{in}$.

Calculate the first derivative of $f_1(T)$ and $f_2(T)$ respectively. $\left|f_1'(T)\right| = 1$. In cooling process,

$$\left|f_2'(T)\right| = 4.74 \times 10^{-6} (4.2 \leq T < 20),$$

$$\left|f_2'(T)\right| = 3.06 \times 10^{-5} (20 \leq T < 296).$$

In heating process,

$$\left|f_2'(T)\right| = 5.3 \times 10^{-6} (4.2 \leq T < 296).$$

This proves that the numerator term is more sensitive to changes in ambient temperature. In this way, Equation 3 can be written as Equation 5:

$$R_{th} = \frac{T_j}{P_{in}} - \frac{T_{amb}}{P_{in}} \quad , \quad (5)$$

when the temperature changes by a very small amounts $\Delta T_{amb}$, Equation 5 can be transformed into Equation 6:

$$\Delta R_{th} = \frac{\Delta T_{amb}}{\Delta P_{in}} \quad , \quad (6)$$

the numerator and the denominator are multiplied by $\Delta\lambda$ in unison. Considering that $\Delta P_{in}$ is insensitive to temperature, Equation 6 can be rewritten as Equation 7:

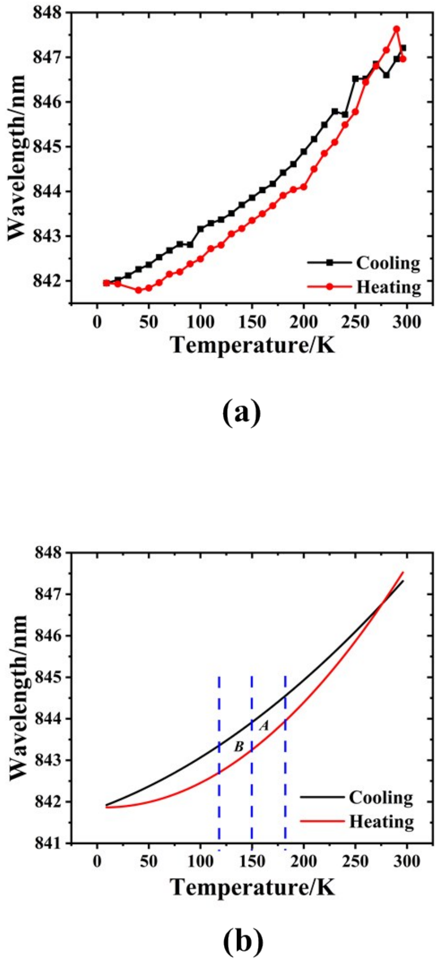
$$\Delta R_{th} \approx C \cdot \Delta\lambda \, \Delta T_{amb} \quad , \quad (7)$$

where, $C$ is a constant; $\Delta T_{amb}$ is the change of ambient temperature; $\Delta\lambda$ is the shift of the spectrum. The thermal resistance can be obtained by integrating Equation 7.

The spectral curve is not coincident during the cooling and heating processes[6]. Theoretically, the curves should be completely coincident at the same temperature with the same conditions. However, the results indicate a thermal hysteresis. It shows that the thermal resistance is different during the cooling and heating process. This disparity can be expressed by the integral differences of curve $\lambda$-$T$ varying with temperatures. The difference is caused by the thermal hysteresis of the package structure. This is the method of wavelength hysteresis to evaluate the heat transfer of the semiconductor laser package in a variable temperature environment.

## 2 Results example and discussion

We found that the spectrum of the laser changes with an ambient temperature in a quadratic relationship as shown in Fig. 2. The same phenomenon also appears in Ref. [19]. In Fig. 2, the injection current is maintained at 10 mA. The ambient temperature is changed in steps of 10 K. The time step of the experiment is nearly 10 min. The package of the laser is TO-Can. The two curves do not coincide. The thermal hysteresis occurs in this process.



(a)

(b)

Fig. 2 The measurement interval is 10 minutes, (a) the central wavelength of the spectrum varies with ambient temperatures during the process of cooling and heating, (b) the results of curves fitted

图2 当测试时间间隔为10分钟时,(a)在降温和升温过程中,光谱的中心波长随环境温度的变化,(b)图(a)中曲线的拟合结果

In the cooling process, the equation of curve fitting is:

$$f(x) = 841.837\,06 + 0.009\,11 \times x^1 + 3.175\,02 \times 10^{-5} \times x^2$$

In the heating process, the equation of curve fitting is:

$$f(x) = 841.867\,34 - 8.870\,47 \times 10^{-4} x^1 + 6.756\,65 \times 10^{-5} \times x^2$$

In Fig. 2(b), two areas are marked with $A$ and $B$. They have the same temperature range of 30 K. According to Equation 7, we calculated the area of two regions. The area of region $A$ is 10. 461 622 K/W. The area of region B is 12. 731 384 4 K/W. Area $A$ is smaller than $B$. It illustrates that the thermal resistance of area $A$ is smaller and the heat dissipation performance is better.

Fig. 3 displays the ratio of $R_{th}$ during cooling to heating varying with the temperatures. The specific value of thermal resistance cannot be calculated because the PN junction temperature is unknown. Nevertheless, in the

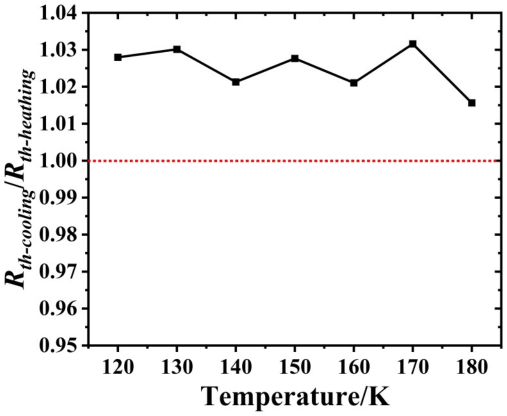


Fig. 3　The ratio of thermal resistance $R_{th}$ during cooling to $R_{th}$ during the heating process varying with the temperatures
图3　降温过程中的热阻$R_{th}$和升温过程中的热阻$R_{th}$的比值随温度的变化情况

experiment of Fig. 2, the test conditions remain unchanged at the same temperature. The cooling capacity of the refrigerator is stable. And the injected current keeps unchanged. Thus, according to Equation 3, the ratio of $R_{th}$ in these two processes could be calculated as shown in Fig. 3. The ratio greater than 1 means the heat dissipation performance in the cooling process is better than that in the heating process. According to the thought of calculus, sum the curves in the range from 125 K to 150 K and from 150 K to 175 K separately. And the results are 4.10701 and 4.09592 respectively. The comparison results can determine that the heat dissipation performance of area *A* in Fig. 2 is better.

For the semiconductor laser, the thermal resistance is divided into three parts, including the thermal resistance between the tube core and the tube shell, the thermal resistance between the tube shell and the radiator, and the thermal resistance between the radiator and the environment. When the directly modulated laser works in optical interconnection from 296 K to 4 K[10], the thermal resistance between the core and the shell should be concerned.

Although the method of measuring thermal resistance by thermal hysteresis mentioned above is derived from the concept of steady-state thermal resistance, it is still applicable to the measurement of transient thermal resistance. When the device works in a high-speed modulated signal, the junction temperature is related to the electric power and the modulated signal. The junction temperature is affected by the waveform, frequency, and pulse width of the modulated signal. The concept of steady-state thermal resistance is no longer used, and the method of the thermal curve analysis mentioned in Ref. [16] is no longer applicable.

However, the result of Equation 7 is an integral unit, independent of time and loading signal, so the method in this paper is also applicable to the evaluation of transient junction temperature.

When the step size changes from 10 min to 120 min, the center wavelength of spectral varying with the temperature is shown in Fig. 4.

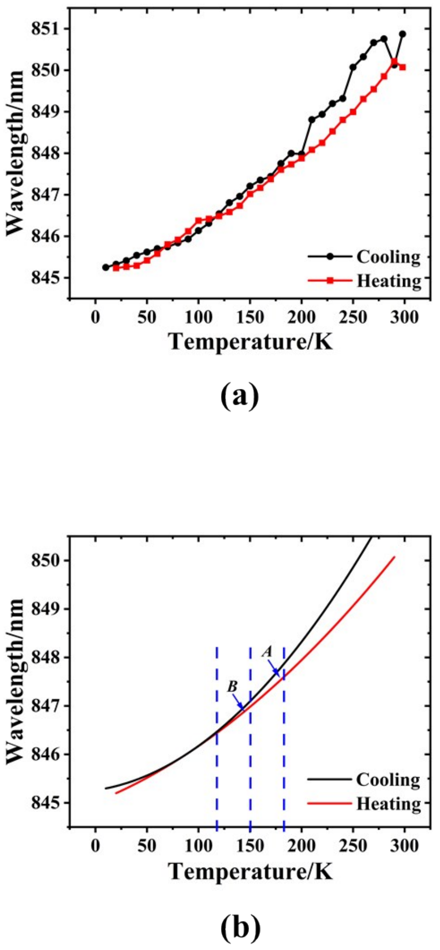


Fig. 4　The measurement interval is 120 minutes, (a) the central wavelength of the spectrum varies with temperatures, (b) the results of curves fitted
图4　当测试时间间隔为120分钟时,(a)在降温和升温过程中,光谱的中心波长随环境温度的变化,(b)图(a)中曲线的拟合结果

The interval of ambient temperature change is long enough, and the packaging of the device has sufficient heat exchange. From 200 K to 10 K, the two curves coincide. This is different from Fig. 2. We fit the curves; the results are shown in Fig. 4(b).

For the result of the cooling process, the equation of curve fitting is as follows:

$$f(x) = 845.260\,81 + 0.002\,95 \times x^1 + 6.177\,68 \times 10^{-5} \times x^2$$

For the result of the heating process, the equation of curve fitting is as follows:

$$f(x) = 845.016\,61 + 0.008\,44 \times x^1 + 3.099\,15 \times 10^{-5} \times x^2$$

The area of region *A* is 5.3637 K/W. The area of region *B* is 1.9927 K/W. Area *B* is smaller than *A*. It illustrates that the thermal resistance of area *B* is smaller and the heat dissipation performance is better. In Fig. 4

(a), the two curves nearly coincide, which indicates that area $B$ has a lower $R_{th}$. The results in Fig. 4 are closer to the steady-state thermal resistance of the laser.

## 3 Summary

The semiconductor laser technology based on room-temperature optical interconnection has been relatively mature, including the design and fabrication of laser packages. From 296 K to 10 K, the package impacts on the performance of the semiconductor laser. In particular, many thermal resistance parameters are related to the ambient temperatures. The existing methods are difficult to apply to a low-temperature environment. Besides, there is no suitable method to measure the thermal characteristics of the laser.

In this article, the method of wavelength hysteresis is used to characterize the thermal resistance of the semiconductor lasers. This method converts thermal resistance calculation into the spectral measurement. It is suitable for the laser working in a low-temperature environment. This study extends the investigation of laser thermal effects from room temperature to 10 K. This is of great significance for realizing optical interconnection between low temperature and room temperature. It is also helpful for package design of semiconductor lasers at low temperature.

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