Nondestructive Measurement for Front Facet Temperature of Semiconductor Lasers

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Abstract. A convenient, simple method is proposed to measure the front facet temperature, which is the highest temperature in the semiconductor laser diode (LD), of a GaAs-based laser by employing thermoreflectance technique. Using an optical system featured in fiber connection, we measured the facet reflectivity of the 808-nm AlGaInAs/AlGaAs LD, which gives information about the temperature of the output facet. The fiber system operates at the wavelength of 1550 nm which avoids the absorption of the probe beam by the tested LD and consists of a fiber-coupled 1550 nm laser illuminant and photodiode. All optical elements in the system are connected by the fibers. The current signal collected from the photodiode is related to the facet reflectivity and represents facet temperature. We compared the facet temperatures determined by thermoreflectance technique with the cavity temperature obtained by forward-voltage method and found that the former is as much as three times as the latter.

1. Introduction
The inner temperature of device critically affects the performance and lifetime of semiconductor laser diodes (LDs). Temperature rise will lead to undesired device degradation such as the reduction of luminous power and electro-optic conversion efficiency. High temperature is even likely to cause device failure such as catastrophic optical mirror damage (COMD) under high power operation [1]. To understand and overcome this problem and optimize the devices, it is necessary to study the thermal characteristics, and an important and efficient step is temperature measurement. Inner active region temperatures can be obtained by measuring the forward voltage [2]. Along cavity of the semiconductor lasers, the temperature maximum and secondary peaks are located at the two facets [3]. Previously several groups have reported temperature measurements in different semiconductor diode laser structures employing variety of detecting such as micro-Raman spectroscopy, photoluminescence, and IR thermography, although direct measurements of facet temperature in lasers by IR thermography have shown low spatial resolution, and the former two have been limited to a low temperature resolution and require relatively intense pump light which can cause additional heating and affect accuracy [4,5,6].

Thermoreflectance is a well-established temperature measurement technique for micro-electronic and opto-electronic devices due to its high spatial resolution (micrometer and even sub-micrometer scale), high sensitivity (better than 1K) [7, 8], and relatively short experiment time; therefore, it has been explored to determination of the facet temperature in numeric reports. The basic idea is to measure the slight change $\Delta R$ in reflection $R$ of a sample surface caused by temperature variation $T$. The relationship is linear for small temperature variations and is given by $\Delta R/R = \kappa \Delta T$. The thermoreflectance
coefficient $\kappa$ depends upon both the material and the wavelength of the probe beam. It can be measured using thermocouples as part of a calibration procedure. For some applications of thermoreflectance technique, probe beam incidents obliquely on the sample surface then is reflected and received in the symmetrical direction [9], but it is more common beam incidents vertically with a polarizing beam splitter and waveplate to separation incident and reflected light [7,10]. However, in both situations, each component on the optical path must be placed strongly accurately to ensure the correct angle of the beam, which raises the difficulty of experiment. Besides, almost all probe beam wavelengths in those cases are 457.9 nm–670 nm in the visible light wave band, while the emitting wavelengths of the tested lasers vary from 808 nm to 1550 nm [11]. The absorption of the probe beam by the active region materials may cause additional heating.

In this paper, we propose a convenient and simple method and a system based on thermoreflectance and fiber detection to measure the temperature variation on the front facet of active region of semiconductor lasers. The facet reflectivity of the 808-nm AlGaInAs/AlGaAs LD under operation is monitored by an optical system consisting of a 1550 nm laser diode illuminant and photodiode. The test beam’s energy is less than the bandwidth of the material in the active region of the tested laser, therefore it will not be absorbed. All optical elements in the system are connected by fibers and thus do not need to be strictly arranged like those in traditional cases. The front facet temperatures determined by thermoreflectance technique are compared with the cavity temperature obtained by forward-voltage method and the result shows that the former can be as much as three times as the latter.

2. Samples and Experimental Arrangement
Broad-area GaAs-based LDs emitting at 808 nm with a single quantum well and edge-emitting structure is investigated in this study. A 3-µm thick epitaxial layer consisting of 1-µm-thick AlGaAs claddings and 0.5-µm-thick AlGaAs waveguides on both sides, with a 2-nm-thick AlGaInAs quantum well in the center, is grown on a 120-µm-thick GaAs substrate by metalorganic chemical vapor deposition (MOCVD). Above the p-waveguide layer are the GaAs cap layer and the insulating layer. A channel is photolithographed in the middle of the insulating layer to concentrate the injection current in the channel; therefore, the light-emitting region is concentrated in the active layer below the channel. The front and rear facets are coated with 100-nm-thick and 120-nm-thick Al$_2$O$_3$/Si films, and their respective reflectivities are <10% and >98% at 808 nm. The chip is welded p-side-down with an in solder to a Cu heat sink. The emitter stripe width and the cavity length are 100 µm and 2 mm, respectively, and the width of the whole laser chip is 500 µm. Figure 1(a) shows the chip structure of the studied samples.

Figure 1(b) shows a schematic diagram of the entire experimental system. First, a 1550 nm test laser beam produced by a fiber-coupled laser diode enters from port 1 and is transmitted to port 2 through a one-way circulator. This test laser beam then passes through a Berkeley packet filter (BPF) into a fiber pigtail and incidents to the front facet of the tested 808 nm LD. Because the pigtail is vertically aligned with the active region of the facet, the light reflected by the surface will enter the pigtail again. The 1550 nm test beam returns to the BPF to exclude the 808 nm laser signal coming from the LD, which ensures the detection of purely 1550 nm test beam radiation in the optical system. Subsequently, the reflected test beam enters the circulator from port 2 is and sent via port 3 to a 1550 nm fiber-coupled photodiode, in which the light is converted into a photo-current signal that carries the facet temperature information. Since the energy of the test beam is less than the bandgap of the 808 nm LD, the measurement is nondestructive and able to keep accuracy without the test beam being absorbed and causing additional heating. The power of the 1550 nm test beam is 2.5 mW, highly larger than that of the 670 nm light used to investigate 980 nm LD as Ref.7 reported. This is because we do not need to use weak test light to reduce the influence of the additional heating caused by absorption, which also enhances the intensity of the signal to be detected later.
In the actual experiment situation, the end of the pigtail was placed very close to the front facet so as to shorten the propagation distance and reduce the propagation loss of the test beam [12], but did not touch the facet. The laser under test was fixed, while the pigtail was placed in a freely adjustable frame. An optical meter was used to perform reflectivity measurements toward the laser facet and help pigtail to align with the 100 µm active region vertically. At this time, the port 3 of the circulator was connected to the optical power meter instead of the photodiode. When the indication of the optical power meter is maximum in the process of adjusting the pigtail, it means the pigtail was perpendicular to the front facet. The optical power meter was then replaced with the photodiode for subsequent temperature measurement.

Before the facet temperature measurement, we need to determine thermoreflectance coefficient $\kappa$ which depends on both the material and the wavelength of the test beam. The tested laser is placed on a constant temperature water-cooled platform. The current temperature of the constant temperature platform is adjustable, and the reflectivity of the 1550 nm incident light on the facet of the tested device is measured under different temperature conditions. The coefficient can be obtained by fitting the reflectivity-temperature curve. The determined thermoreflectance coefficient $\kappa$ is $2.27 \times 10^{-4}$ shown in figure 2 (a), clearly exhibiting a linear relationship between the temperature and reflectivity.

During the measurement, the constant temperature platform is controlled at 25 ℃, and the laser is driven by a square wave current with a frequency of 200 Hz, which is also monitored by the oscilloscope. The luminescence of the laser will produce heat, which will cause the temperature rise and the reflectivity to change. The reflected photocurrent is monitored by the oscilloscope, and the change of facet reflectivity is available from the oscilloscope. According to the thermoreflectance coefficient $\kappa$ determined in the previous step, the facet temperature, which is the highest temperature of the laser in the operation state, can be calculated.
We measured the inner cavity temperature by using the forward voltage method. It is an electric method and its basic is the linear relationship between junction voltage and junction temperature in PN junction. This method measures the average temperature of the active region. Like the facet temperature measurement, the temperature coefficient is determined before actually measuring the inner cavity temperature. As shown in figure 2 (b), the junction voltage of the device is obtained under different temperature conditions, and then the coefficient is fitted as -2.35 mV/℃. When measuring the temperature of the inner cavity, the temperature of the laser substrate is also 25 ℃.

![Graphs showing temperature changes](image)

**Figure 2.** (a) thermoreflectance coefficient $\kappa$. (b) temperature coefficient.

### 3. Results and Discussion

![Graphs showing current variations](image)
Figure 3. (a)-(c) facet temperature and driving current of square wave or sine wave with different frequencies. Labels of the curves are removed in (b).

The figure 3(a)-(b) shows the facet temperature when the driving current amplitude is 40 mA and 60 mA. The frequency and phase of the blue temperature curve are consistent with those of the red current curve. Because the temperature is modulated by the driving current and the reflectivity is modulated by the temperature, the two curves displayed on the oscilloscope are in the same frequency and phase. Obviously, the facet temperature at 60 mA driving current is higher than 40 mA; the amplitude of the former is 0.6 ℃, and the latter is 0.38 ℃. Because the driving current is very small at this time, the temperature rise is also very small.

When the driving current is a sine wave with a frequency of 1kHz, the reflectivity of the facet still shows a good follow-up to the driving current. However, although they are of the same frequency, there are some small differences in phase. This is because the generation and dissipation of heat require a delay time, which can be seen from the figure 3(c) as about 100 microseconds. The figure 3(c) is obtained when the sampling rate of the oscilloscope is 2.5 MHz, and the curve on it only covers the time length of 4 ms. Therefore, the time of about 100 microseconds is obvious in the figure. The time length covered in figure 3(b) is five times that of figure 3(c), and the sampling rate is one fifth, so the delay time is not obvious.

Figure 4 shows the comparison of facet temperature and inner cavity temperature. The facet temperature is almost always higher than the inner cavity temperature, and the gap between them increases with the increase of the driving current. When the driving current is 360 mA, the facet temperature is three times higher than the inner cavity temperature. This is because the defect at the facet of the semiconductor lasers will become the light absorption center, where the carriers generated by light absorption produce non-radiation and release heat [13, 14].
4. Conclusion

We use a technique to measure the temperature of the front facet of semiconductor lasers. This technique is noncontact and nondestructive because it is based on thermoreflectance and the wavelength of the probe light is longer than the emitting wavelength of the device to be tested. This technology is also very convenient because of the use of fiber-coupled lasers and photodiodes. Using this method, the thermoreflectance phenomenon is observed in both situation when the driving current is square wave or sine wave with different frequencies, and the facet temperature is measured. When the driving current frequency is high, a delay time of about 100 microseconds can be observed between the reflectivity curve and the current curve. The temperature of front facet is higher than that of the inner cavity, even up to three times the latter.

References

[1] Perlin P et al. 2008 Fabrication and properties of GaN-based lasers J. Cryst. Growth 310 (17) 3979-82.
[2] Feng M X, Zhang S M, Jiang D S, Liu J P, Wang H, Zeng C, Li Z C, Wang H B, Wang F, Yang H. 2012 Thermal characterization of GaN-based laser diodes by forward-voltage method J. Appl. Phys 111 (9) 094513.
[3] Shi D, Feng S W, Qiao Y B, Wen P Y. 2015 The research on temperature distribution of GaN-based blue laser diode Solid-State Electron 109 (1) 25-8.
[4] Sweeney S J, Lyons L J, Adams A R and Lock D A 2003 Direct measurement of facet temperature up to melting point and COD in high-power 980-nm semiconductor diode lasers IEEE J. Sel. Top. Quantum Electron 9 (5) 1325-32.
[5] Tang W C, Rosen H J, Vettiger P and Webb D J. 1991 Raman microprobe study of the time development of AlGaAs single quantum well laser facet temperature on route to catastrophic breakdown Appl. Phys. Lett 58 (6) 557-9.
[6] Kozłowska A, Latoszek M, Tomm J W, Weik F, Elsaesser T, Zbroszczyk M, Bugajski M, Spellenberg B and Bassler M 2005 Analysis of thermal images from diode lasers: Temperature profiling and reliability screening Appl. Phys. Lett 86 (20) 203503.
[7] Dacal L C O, Mansanares A M and Da Silva E C 1998 Heat source distribution, vertical structure, and coating influences on the temperature of operating 0.98 mm laser diodes: Photothermal reflectance measurements J. Appl. Phys 84 (7) 3491-9.
[8] Chan P K L, Pipe K P, Mi Z, Yang J, Bhattacharya P and Lüerßen D 2006 Thermal relaxation time and heat distribution in pulsed InGaAs quantum dot lasers Appl. Phys. Lett. 89 (1) 011110.

[9] Fournier D and Forget B 1991 Thermal wave probing of the optical, electronic and thermal properties of semiconductors J. Phys. IV 01 (C6) 241-52.

[10] Epperlein P W 1993 Micro-temperature measurements on semiconductor laser mirrors by reflectance modulation: a newly developed technique for laser characterization Jpn. J. Appl. Phys 32 (12A) 5514-22.

[11] Pierścińska D 2018 Thermoreflectance spectroscopy—Analysis of thermal processes in semiconductor lasers J. Phys. D: Appl. Phys 51 (1) 013001.

[12] Zhang S Y, Feng S W, Zhang Y M, An Z F, Yang H W, He X, Wang X and Qiao Y B 2017 Monitoring of early catastrophic optical damage in laser diodes based on facet reflectivity measurement Appl. Phys. Lett 110 (22) 223503.

[13] Nakwaski W 1985 Thermal-analysis of the catastrophic mirror damage in laser-diodes J. Appl. Phys 57 (7) 2424-30.

[14] Epperlein P W and Bona G L 1993 Influence of the vertical structure on the mirror facet temperatures of visible GaInP quantum well lasers Appl. Phys. Lett 62 (24) 3074-6.