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Electrical Derivative Measurement of High-Power InGaAs LDs Under Scanning Current with Variable Step*

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Abstract — For the large driving current of high-power semiconductor Laser diodes (LDs), a modified method to measure the electrical derivative of LDs under scanning driving current with variable step length is proposed, which is to achieve the fast and accurate measurement of optical and electrical characteristic parameters of LDs with a relatively small data acquisition. The experimental results show that, with fewer measurements, this method can effectively and accurately measure and extract the LDs corresponding parameters including threshold current (I_{th}), voltage-current characteristic (V-I), luminous power-current relation (P-I), electrical derivative curve (IdV/dI-I). The wavelet transformation singularity testing results of the threshold current also verify the accuracy, reliability, and advantage of this method.

Key words — Semiconductor laser diodes (LDs), Electrical derivative, Scanning current, Wavelet transform, Singularity detection.

I. Introduction

Semiconductor Laser diodes (LDs) are broadly applied in material manufacture, communication, measurement and many other fields due to the advantages including small size, long lifetime and so on[1−6]. With the development of semiconductor and photo electronic technologies in recent years, new breakthroughs have been constantly made on LDs, such as double hetero junction LDs, quantum well LDs, quantum cascade LDs[7−12], which further reduce the threshold current of devices, optimize the temperature stability, improve the electro-optical conversion efficiency. At present, power semiconductor laser is one of the main researching directions[13]. For high power semiconductor LDs, it is of great significance to study a quick and efficient method to acquire the device characteristic parameters in larger driving current.

The derivative technique, as a nondestructive testing method for LDs reliability, has aroused broad attention[14]. Since Barnes *et al.* first proposed the theory to use the derivative method to evaluate the reliability of LDs[15], some related methods are continuely proposed, such as using the saturation characterisitcs of the junction voltage to test the double heterojunction LDs[16], an equivalent circuit model based on the derivative method of bury heterojunction InGaAsP LDs[17], and Choy from the Bell Labs proposed the screening method for the fast degradating devices using the derivative parameters before and after the threshold current[18]. However, the fixed step scanning current method is still being used for the measurement of the electrical derivative of semiconductor LDs[19−24], which is suitable for low-power devices, but for the derivative measurement of high-power devices, due to the high threshold currents, the driving current variation range is much wider, the measuring time is longer and the acquired data is more, so the measuring efficiency is low. Besides, the measurement under long-time large current can cause internal damage in devices, which may reduce the lifetime of the devices, so it is a significant work to quickly and accurately extract the electrical derivative

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parameters to evaluate the reliability of LDs with less data acquired. All the current electrical derivative measurements still adopt the method with fixed step scanning current, *i.e.*, the driving currents increasing in a fixed step are applied on LDs to acquire the terminal voltages and laser powers under each current, and the curves of voltage-current($V-I$) and power-current($P-I$), from which the parameters being closely related to the reliability of the LDs can be extracted, including the threshold current, sinking height at the threshold, junction characteristic parameter and the derivative intercept after the threshold[20].

In this paper, we propose a novel derivative measuring method under scanning current with variable step for the large driving current of high power semiconductor LDs to realize a quick extraction of the parameters with less measurement data. First the LDs are tested by a scanning current with longer step in the whole current range to roughly acquire the threshold interval, and then in this interval the derivative is measured again under a scanning current with shorter step, which not only the overall information of the derivative out of the threshold interval is acquired, but also the detail information near the threshold. The experimental results show that this method can more efficiently and accurately extract the derivative parameters of LDs.

II. Method and Experiment

The extraction of the electrical derivative parameters of semiconductor LDs mainly includes the curve measurements of the derivative and laser power versus the driving current. The derivative is the product of the driving current I and, the differentiation, dV/dI, of the terminal voltage V to I, and the equations before and after the threshold current I_{th} can be expressed as below[14]

$$I\frac{dV}{dI} = IR_S + \frac{mkT}{q}, \quad I < I_{th} \tag{1}$$

$$I\frac{dV}{dI} = IR_S, \quad I \geq I_{th} \tag{2}$$

Where R_s is the equivalent series resistance of the LDs. The photoelectric characteristics curves of ideal semiconductor LDs are shown in Fig.1 where curve 1, 2, 3 and 4 are respectively corresponding to the voltage-current(V-I) characteristic, laser power(P-I), derivative(IdV/dI-I) and the second derivative of the laser power(d^2P/dI^2-I). The threshold current I_{th} is extracted from the d^2P/dI^2-I curve. According to Eq.(1), there is a sink in the derivative curve at the threshold current, the height of which is the junction voltage saturation depth. The slope of the derivative curve below the threshold represents the equivalent series resistance R_s of LDs, and the intercept of the curve before the threshold is mkT/q, which is used in extracting the junction characteristic parameter m, and the intercept after the threshold b represents the junction integrity and the carrier leakage. The parameters above can be acquired by measuring the V-I curve and the P-I curve, and the two curves are usually measured under a scanning current with a fixed step.

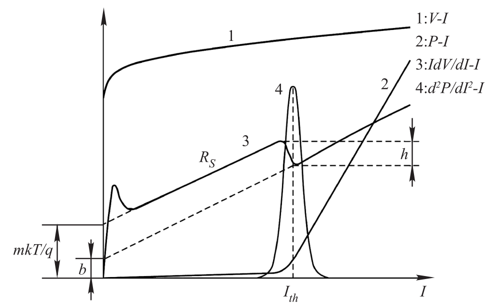


Fig. 1. The photoelectric characteristics curves of ideal semiconductor LDs

The principle of scanning driving current with variable step is shown in Fig.2. Theoretically, the information is more abundant near the threshold current, so the scanning current step should be shorter, and the photoelectric characteristics curves in other intervals change relatively more slowly versus the current, so the step can be longer, so that it can be ensured that the parameters are extracted more accurately with less data. The specific process of our method is to first scan the whole current range with a long current step, and by computing the second derivative of the laser power versus I, a threshold current I_{th} is roughly estimated, and then an interval (I_L, I_H) containing I_{th} is scanned with a shorter and refine step while the data in other intervals remain the same. At last the data acquired by the scanning are computed to get the precise threshold current and other parameters.

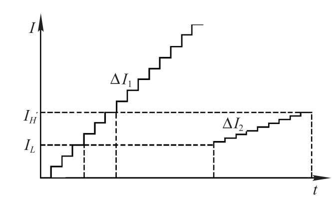


Fig. 2. The principle of scanning driving current with variable step

The schematic of the testing system is shown in Fig.3, where the MCU with 32-bit ARM9 core is used as the core controller, the voltage-control constant current source is used as the actuator to realize the digital driving, the laser power(represented by voltage) of the device is measured by the photodiode as the sensor, and the AD conversion precision of the terminal voltage and the laser power is 12 bit. The experimental samples are InGaAs quantum well high-power semiconductor LDs of which the power is 3W, the laser wavelength is 976nm, the cavity length is 2000um, the quantum well width is 10nm and the threshold current is 300mA, manufactured by the China Electronics Technology Group Corporation.

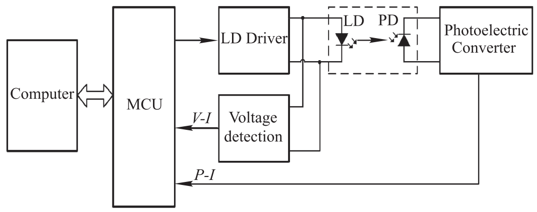
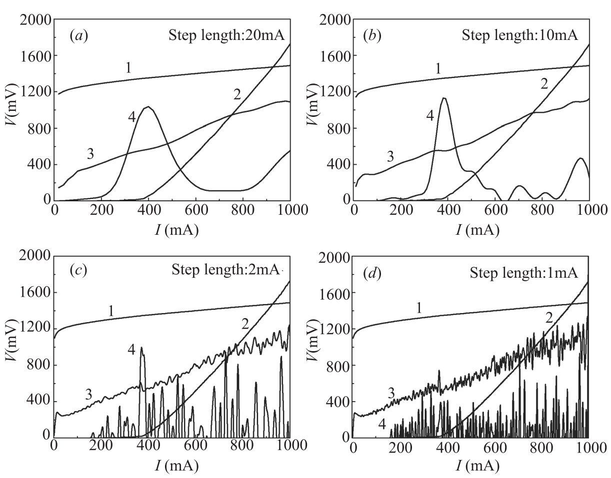


Fig. 3. The schematic of the testing system

III. Experiment Results and Analysis

In order to investigate the influence of the step length on the measurement results, the photoelectric characterisitcs of LDs measured by different fixed steps are shown in Fig.4, where Fig.4(a)–4(d) are corresponding to the steps of 20mA, 10mA, 2mA and 1mA and curve 1–4 are the V-I, P-I, IdV/dI-I and d^2P/dI^2-I curves. From Fig.4(a)–4(c) we can directly see that, when the step decreases, the peak of the d^2P/dI^2-I curve at the threshold current narrows down, which indicates that the extracted threshold current is more accurate, and meanwhile the sink of IdV/dI-I curve is more distinct. However, from Fig.4(d) we can see that when the step further decreases, the noise of the measured data increases distinctly, and the important information such as the peak and the sink are drenched in the noise, which inevitably cause the inaccuracy or even incapability of the parameter extraction.



1: V-I; 2: P-I; 3: Idv/dI-I; 4: d^2P/dI^2-I

Fig. 4. The photoelectric characterisitcs of LDs measured by different fixed steps

This phenomenon above can be explained through the filtering of the signal derivation. The derivation of a signal is actually a filtering process, and taking the derivation dV/dI for example, the amplitude-frequency responses of the filters corresponding to different current steps in this process are shown in Fig.5, where the frequency axis is normalized and f_s is the reciprocal of the minimum current step(ΔI=1mA) in the experiment, which we call the max sampling frequency. From Fig.4 we can see that the shorter the scanning current step is, the wider the bandwidth is, the larger the filter central frequency is, and the weaker the suppression to the high frequency signal. There are inevitably noise and interferences in actual experiment system, which mostly exist as the high frequency component, and the magnitude spectra of the V-I data of the LDs is shown in Fig.6, from which we can see that most of the signal components are in the low frequency band, and the high frequency components are mainly the noise and the saltation component at the threshold current. Therefore, the longer current step can effectively suppress the noise but the sink at the threshold is more obscure (Fig.4(a)–4(c)), and steps too short will cause the useful signal components drenched in the noise(Fig.4(d)), so appropriate current steps are of great significance for accurately extracting the parameters during the actual measurements.

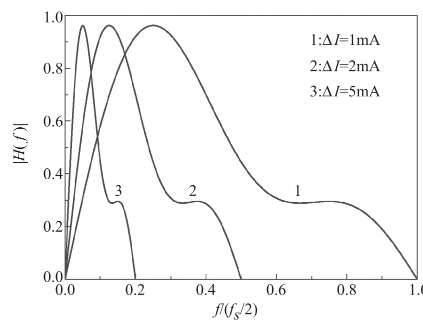


Fig. 5. The amplitude-frequency responses of the filters corresponding to different current steps

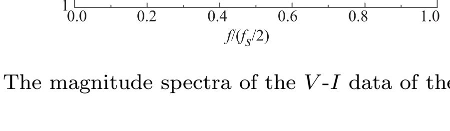


Fig. 6. The magnitude spectra of the V-I data of the LDs

In order to accurately acquire the information of threshold current and the derivative sink at the threshold and so on with less sampling points and effectively suppress the noise, we propose the measuring method under scanning current with variable step. First a sampling process is conducted in the current interval of 0–1000mA with the current step of ΔI_1=10mA (100 points), and after generally estimating the threshold current I_{th}', a refiner sampling process is conducted in the current interval of (I_{th}'-50,I_{th}'+50) with the current step of ΔI_2=2mA (50 points), so only 150 points are sampled in total, and then the accurate threshold I_{th} can be acquired. The measurement results are shown in Fig.7, from which we can obviously see that the noise of the curves is effectively suppressed, and the peak in the d^2P/dI^2-I is very distinct, which indicates that the threshold current is accurately extracted, and the derivative sink at the threshold is also very distinct.

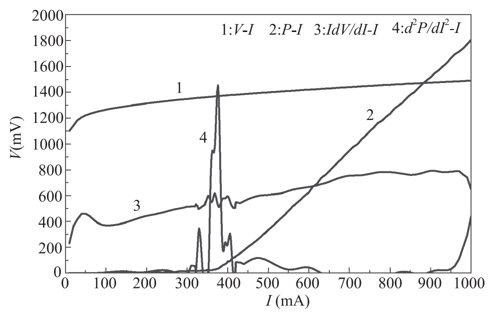


Fig. 7. The result of variable step scanning current drive method

Next in the quantatively comparison among the measurement results above, we use the derivative slope at the threshold ($d(IdV/dI)/dI|_{I=I_{th}}$) to represent the obviousness of the derivative sink, the half-peak bandwidth($2\Delta I_{0.5}$) of the d^2P/dI^2-I peak at the threshold and the $I_{th}/2\Delta I_{0.5}$ (we call it Quality factor) to represent the accuracy of the threshold current extraction, to compare and analyze the different fixed steps and variable step methods. In fact, the negative $d(IdV/dI)/dI|_{I=I_{th}}$ indicates that the threshold derivative sink appears, the larger its absolute value is, the more distinct the sink is. Besides, the smaller $2\Delta I_{0.5}$ is and the larger $I_{th}/2\Delta I_{0.5}$ is, the narrower and steeper the peak is, which indicates that the acquired threshold current is more accurate. The comparison results are shown in Table 1, from which we can see that the accurate parameters cannot be acquired whether the current step is too long or too short, and the results of variable step method is almost the same as the 2mA step, meanwhile our method acquired the results with only 150 sample points instead of the 500 points in the fixed step method, which is entirely coherent to the expected result.

Table 1. The comparison results of different fixed steps and variable step methods

Scanning current step ΔI(mA)	Sample point amount N	Threshold current I_{th}(mA)	$d(IdV/dI)/dI\|_{I=I_{th}}$	d^2P/dI^2 half-peak bandwidth $2\Delta I_{0.5}$(mA)	quality factor I_{th} /$2\Delta I_{0.5}$
20	50	400	0.75(failure)	180	2.22
10	100	380	-0.05	90	4.22
5	200	380	-1.97	40	9.50
2	500	372	-12.35	24	15.50
1	1000	-	-	-	-
Variable	150	376	-14.12	26	14.46

For some LDs with nonlinear $P-I$ curve, we can still acquire their threshold currents and electrical derivative curves using the variable step method. Multiple measurements confirm that variable step method applies to nonlinear P-I curve LD.

The derivative measuring method above requires the laser power curve first to get the accurate threshold current. In order to simplify the measurement system and lower the measuring difficulty and further testify the accuracy and superiority of our variable step method, the measurement of the laser power can be avoided, and the threshold current can be directly extracted from V-I curve by using wavelet singularity detection[25−26]. The wavelet transformation results of the 10mA and 2mA step V-I curve under different scales are shown in Fig.8 and Fig.9 and the results of the variable step method are shown in Fig.10, where $W^d_{2^j}V$ represents the binary wavelet transformation of $V(I)$ with scale j and time shift d. During the computation of the wavelet coefficients of the variable step method, the original signal needs to be linear interpolated to make the data be a uniform distribution on the current axis. Obviously, in Fig.8 the maximum value of the wavelet coefficient module (threshold current I_{th}) is vague, and in Fig.9 the threshold current cannot be detected because of the interference of the high frequency components, however, from Fig.10 we can see that all the wavelet coefficient curves appear to have speculate maximum module points and the high frequency noise interferences are effectively suppressed. These results are coherent to the former measurements in Fig.4 and Fig.7.

According to the analysis above, all the experiment results show that the variable step method can accurately measure and extract the derivative parameters of the LDs with less measured data, and possess the advantages such as high accuracy, reliability and so on. Not only can the variable step method accurately acquire the LD photoelectrical characteristics, it can also quickly determine whether the device is damaged. The LD can be confirmed damaged within the following circumstances: 1) The threshold current cannot be acquired when there is LD luminous power output; 2) The V-I curve is normal when there is no LD luminous power output; 3) LD is damaged by large bias current overload or high temperature; 4) The circuit is open because the LD damage, when there is no LD luminous power output and the V-I curve cannot be acquired.

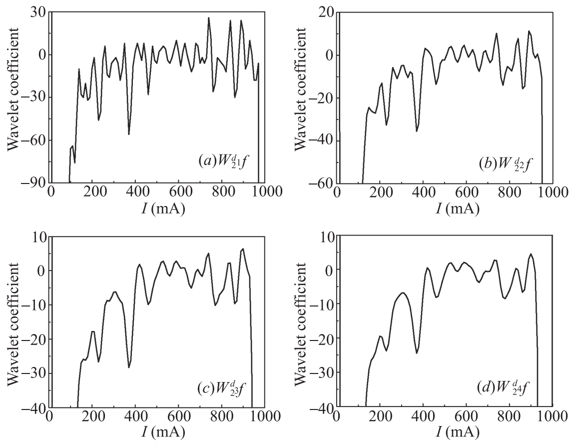


Fig. 8. The wavelet transformation results of the 10mA current step

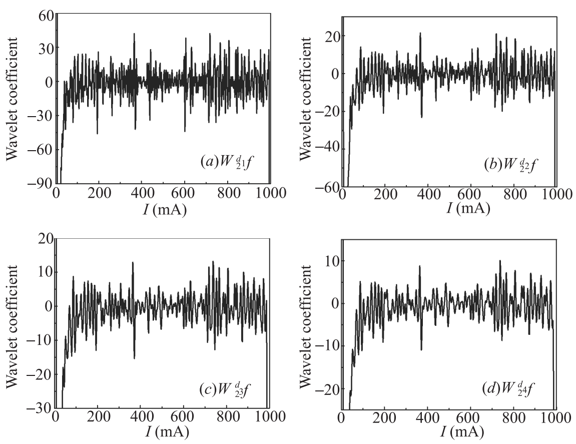


Fig. 9. The wavelet transformation results of the 2mA current step

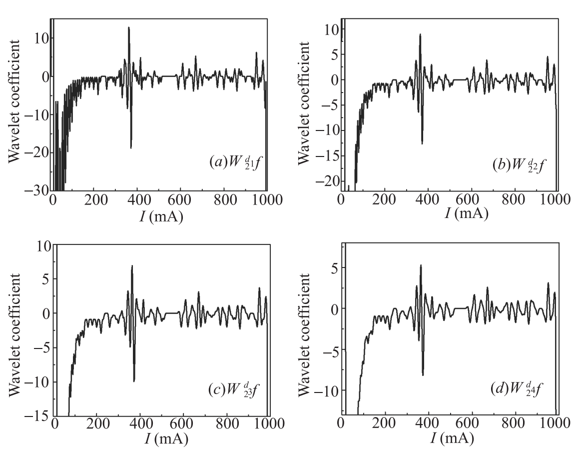


Fig. 10. The wavelet transformation results of the variable current step method

For the first two cases, this method cannot detect the peak of d^2P/dI^2-I and the threshold current, but can acquire a rough derivative curve. And for the latter two cases, the LD is broken during the first scanning so the second scanning cannot proceed, therefore the electrical derivative curve cannot be acquired but an approximate threshold current. In brief, if the threshold and the whole electrical derivative curve cannot be acquired, it can be determined that the LD device is damaged.

IV. Conclusions

We propose a derivative measuring method for high-power semiconductor LDs under scanning current with variable step. In quantatively comparison to the LDs parameters such as the electrical derivative slope at threshold, the half-peak bandwidth of the d^2P/dI^2-I peak and its Quality factor($I_{th}/2\Delta I_{0.5}$) and so on measured by the fixed step method, we find that our method can extract the threshold current more accurately and obtain a more distinct sink on electrical derivative curve at the threshold. The experiment results show that our method can achieve almost the same measurement results with only 150 sampling points as the fixed step method with 500 sampling points. Furtherly, the threshold singularity testing results of wavelet transformation also verify the accuracy and reliability of this method. Therefore, the experiment results above indicate that our method can accurately and efficiently measure the derivative curve of the LDs and extract the corresponding parameters, and that the measuring time and data storage are remarkably reduced meanwhile.

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