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NOISE MEASUREMENTS OF InGaAsP / InP LASER DIODES NEAR THE THRESHOLD CURRENT

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Investigation of noise characteristics of InGaAsP / InP multiple-quantum-well laser diodes (LDs) near the threshold current region with the aim to reveal the LD quality and reliability problems is presented. A low quality and rapid degradation of particular laser diodes are reflected in noise characteristics: correlation factor between the optical and electrical fluctuations just after the threshold has a deep minimum and even drop to the negative values. The latter values are caused by leakage currents through the defects which determine the low quality and reliability of laser diodes. Optical noise intensity of a semiconductor laser below the threshold (here they operate as light emitting diodes) is low and the own noise level of a photodetector and measurement circuit is equal or exceeds it. In this case the laser diode optical noise has been measured using the correlation function method that increases optical noise measurement sensitivity by about three orders of magnitude.

Keywords: laser diode, noise, cross-correlation function, reliability

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1. Introduction

Laser diode (LD) is one of the key elements in the optical communication systems that nowadays has become a widespread technology for the long-haul and high-bit-rate data transmission as well as for the local area networks [1, 2]. Communication system reliability has to be guaranteed at very high standards, and LDs have to meet high quality requirements: narrow bandwidth, high modulation speed, etc. [3, 4], and they also have to demonstrate a long lifetime [5]. Laser diode lifetime prediction is very important in order to escape system breakdowns and high repairing expenses. For the fabrication of better quality LDs it is important to know the origin of degradation process and its evolution.

The low frequency noise is caused by the reasons that also reduce the semiconductor device quality and reliability [6, 7]. So, it is well known that a noisy device will be less reliable [6, 8]. Besides, the analysis of noise characteristic provides useful information on the physical processes in the device structure and the nature of the noise sources. Our previous works [9, 10] have shown that LD reliability problems reflect in their noise characteristics, too.

In this paper we present a comprehensive investigation of laser diode low frequency noise characteristics in the vicinity of the threshold region, because the threshold is more sensitive to laser structure defectiveness. The investigation was performed in order to clear up the reasons of reliability problems and of rapid degradation of some LDs.

2. Measurement technique

Optical and electrical fluctuations and their cross-correlation factor have been measured and calculated using two identical unrelated channels: one for electrical noise signal (for LD terminal voltage fluctuations), and another for optical noise (for photodetector voltage fluctuation due to LD optical output power fluctuations). Cross-correlation factor is calculated according to the formula

$$r = \frac{k(0)}{\sqrt{\sigma^2_{\mathrm{opt}}\sigma^2_{\mathrm{el}}}}\,, \qquad (1)$$

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where $k(0)$ is the cross-correlation function between two processes at the same time (time shift $\tau = 0$), σ^2_{opt} and σ^2_{el} are the optical and electrical noise variances, respectively.

However, an optical noise signal below the threshold, when a laser diode operates as light emission diode, is masked by the photodetector and measurement system own noises (further: photodetector noise), i. e. the laser diode optical fluctuations comprise just a small part of the measured signal. For the laser diode optical noise measurement in the sub-threshold region, when useful signal is masked by the photodetector noise, the correlation function method was used. In this case LD optical beam is equally directed into two similar photodetectors, and then correlation function between the signals of these photodetectors is computed. Unlike photodetector noise, laser diode noise in both channels is fully correlated. Such method allows us to remove the measurement limitation due to intrinsic noises of photodetectors.

If we denote the total voltages of two photodetectors as $U_1(t)$ and $U_2(t)$, the noise voltages due to the laser diode optical power fluctuations as $U_{\mathrm{opt1}}(t)$ and $U_{\mathrm{opt2}}(t)$, and the own noises of photodetectors as $U_{\mathrm{pd1}}(t)$ and $U_{\mathrm{pd2}}(t)$, then

$$U_1(t) = U_{\mathrm{opt1}}(t) + U_{\mathrm{pd1}}(t)\,,$$
$$U_2(t) = U_{\mathrm{opt2}}(t) + U_{\mathrm{pd2}}(t)\,. \tag{2}$$

Cross-correlation function between noise signals of two photodetectors

$$\begin{aligned} k(\tau) &= \langle U_1(t)\,U_1(t+\tau)\rangle \\ &= \langle U_{\mathrm{opt1}}(t)\,U_{\mathrm{opt2}}(t+\tau)\rangle \\ &\quad + \langle U_{\mathrm{opt1}}(t)\,U_{\mathrm{pd2}}(t+\tau)\rangle \\ &\quad + \langle U_{\mathrm{pd1}}(t)\,U_{\mathrm{opt2}}(t+\tau)\rangle \\ &\quad + \langle U_{\mathrm{pd1}}(t)\,U_{\mathrm{pd2}}(t+\tau)\rangle\,, \end{aligned} \tag{3}$$

where the brackets $\langle \cdots \rangle$ denote the statistical average.

As the noises of photodetectors are not correlated, and those noises do not correlate with the noise due to the laser diode optical power fluctuations, then

$$\begin{aligned} &\langle U_{\mathrm{opt1}}(t)\ U_{\mathrm{pd2}}(t+\tau)\rangle\,, \\ &\langle U_{\mathrm{pd1}}(t)\ U_{\mathrm{opt2}}(t+\tau)\rangle\,, \\ &\langle U_{\mathrm{pd1}}(t)\ U_{\mathrm{pd2}}(t+\tau)\rangle\,. \end{aligned} \tag{4}$$

So, the cross-correlation function $k(\tau)$ is equal to the laser diode optical noise autocorrelation function:

$$k(\tau) = \langle U_{\mathrm{opt1}}(t)\,U_{\mathrm{opt2}}(t+\tau)\rangle\,. \tag{5}$$

Applying Wiener–Khintchine theorem the noise spectral density can be calculated as

$$S(f) = \left\langle 4\int_0^T k(\tau) f\tau\,\mathrm{d}\tau \right\rangle, \tag{6}$$

where T is the duration of the investigation process.

The investigated devices are InGaAsP / InP laser diodes with multiple quantum wells: buried heterostructure (BH) and ridge-waveguide (RWG) LDs with distributed feedback (DFB), and Fabry–Perot (FP) lasers. These LDs emitted at 1.5 μm and are fabricated for operation in optical communication systems.

3. Results and discussion

3.1. Optical noise and cross-correlation factor measurements of laser diodes in sub-threshold region

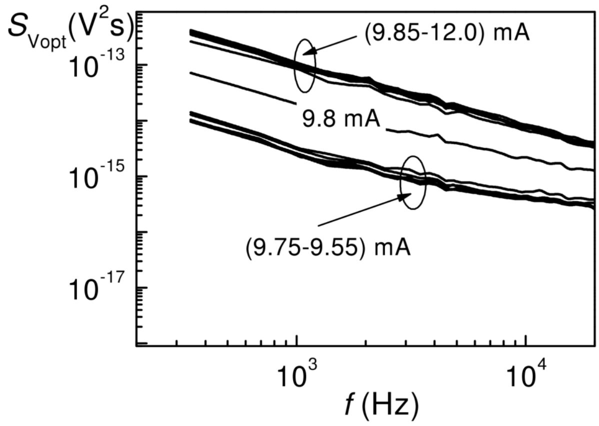
Because the correlation analysis in the threshold region gives more interesting results about electrical and optical fluctuation processes, we also have concentrated our attention on the investigation of LD noise characteristics in the sub-threshold region. While the measurements of laser diode terminal voltage fluctuations do not present any difficulties, the measurement of optical noise in sub-threshold region is related with some problems due to a very low optical noise level.

At the LD operation conditions below the threshold the measured optical channel signal mainly consists of photodetector own noise that naturally is uncorrelated with LD electrical fluctuations. In order to find the real cross-correlation factor, the photodetector noise variance σ^2_{pd} should be subtracted from the total measured optical channel noise variance $\sigma^2_{U1} = \langle (U_1(t))^2 \rangle$:

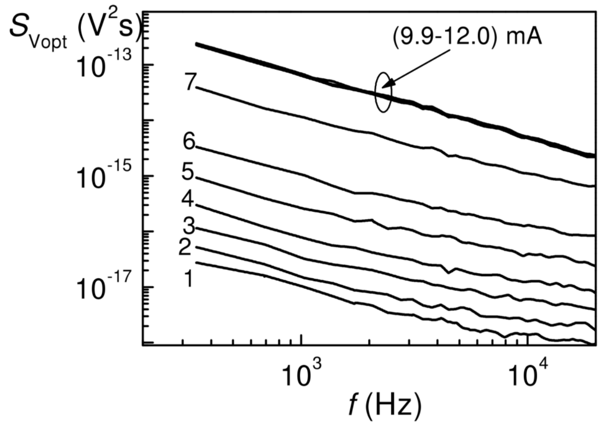
$$r = \frac{k(0)}{\sqrt{(\sigma^2_{U1} - \sigma^2_{\mathrm{pd}})\sigma^2_{\mathrm{el}}}}\,. \tag{7}$$

It has been obtained that the cross-correlation factor between the electrical and optical noises rapidly decreases with current decreasing below the threshold current, and is always positive.

Thus, the optical noise power spectral density below the threshold has been investigated using the correlation function method described in Section 2. The



(a)



(b)

Fig. 1. Optical noise spectra in sub-threshold region estimated by (a) Fast Fourier Transform method (the lower curve presents the noise level of photodetector) and by (b) correlation method, *1* at 9.55 mA, *2* at 9.60 mA, *3* at 9.65 mA, *4* at 9.70 mA, *5* at 9.725 mA, *6* at 9.75 mA, *7* at 9.80 mA; sample: DFB BH LD.

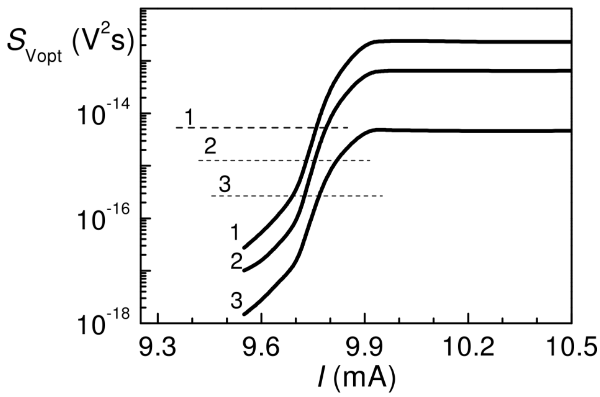


Fig. 2. Optical noise spectral density dependences on laser current measured at threshold region by using correlation method. Solid lines: *1* at 215 Hz, *2* at 1.05 kHz, *3* at 10.3 kHz; dotted lines show the own noise level of photodetector at the same frequencies respectively; sample: DFB BH LD.

advantage of application of the correlation method and statistical averaging for determination of optical noise spectra below the threshold is illustrated in Figs. 1 and 2. They show that the correlation function method allows one to measure optical fluctuations that are at least 2 orders of magnitude lower than the measurement system own noise level. The results of this measurement have shown that the optical noise spectra below the threshold are of $1/f$ type, the same as at lasing operation, and that the noise intensity rapidly decreases with decreasing laser current (Fig. 2).

The optical noise spectra at current over the threshold usually were estimated by Fast Fourier Transform and using statistical averaging, because the optical noise level was much higher than photodetector noise level.

3.2. Laser diode optical and electrical noises and their cross-correlation function in the threshold region

Figure 3 presents typical laser diode noise characteristic changes at the threshold for DFB BH LD (Fig. 3(a)) and FP BH LD (Fig. 3(b)): a steep increase of optical noise for DFB BH LD and a small drop of electrical noise intensity, a positive peak of cross-correlation factor at the threshold and its drop after the threshold; these characteristics of FP BH LD are similar. The correlation factor between optical and electrical fluctuations of laser diode at the threshold has a moderate positive value, ranging from 20% to 70% for different samples (Figs. 3 and 4). After that, the threshold cross-correlation factor has a minimum, which drops even to negative values, and with current increasing further it rises back to the positive values and saturates when the stable lasing operation is achieved. Such cross-correlation factor change with laser current increasing from sub-threshold region to the lasing operation is characteristic of all the investigated laser diodes independently of the laser structure. The observed differences are only in how abrupt and deep is the drop of cross-correlation factor after the threshold and in its value at the stable lasing operation.

Reliable lasers of better quality (the characteristics of which almost have not changed during the ageing procedure) demonstrate lower drop of the cross-correlation factor after the threshold (Fig. 3): i. e., the negatively correlated optical and electrical noise components that are related with leakage currents are less intense.

LDs that have worse operation characteristics or their characteristics rapidly degrade during ageing (3000 h operation at 100 °C and 150 mA forward

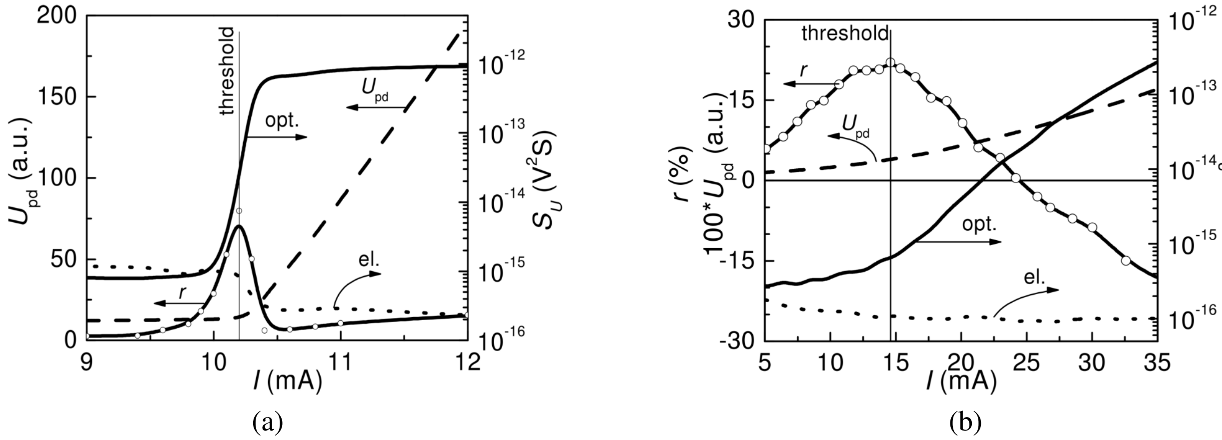


Fig. 3. Typical LD noise characteristic dependences at the threshold for (a) DFB BH LD, (b) FP BH LD samples: r is the cross-correlation factor (frequency range from 20 Hz to 22 kHz), 'opt.' is the optical noise spectral density (1.05 kHz), 'el.' is the electrical noise spectral density (1.05 kHz), U_{pd} is the emitted light power.

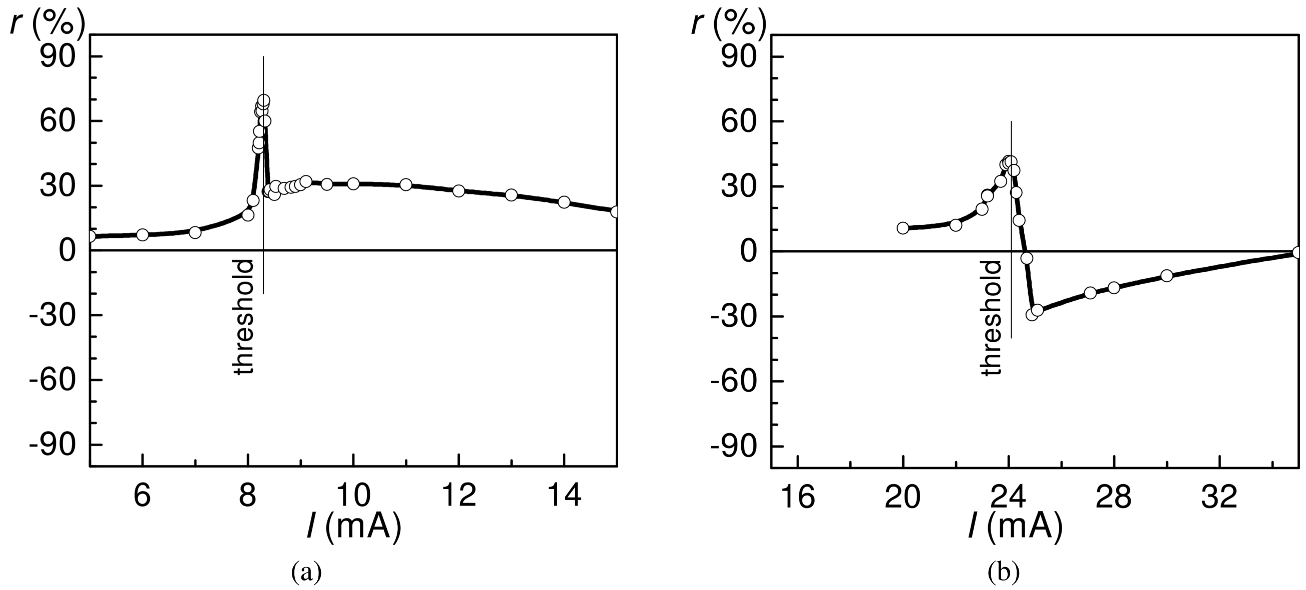


Fig. 4. LD cross-correlation factor dependence on laser current (a) before and (b) after accelerated ageing (frequency range from 20 Hz to 22 kHz, sample: DFB BH LD).

current) demonstrate deep cross-correlation factor drop to the negative values (up to -70%) just after the threshold (graph (b) in Fig. 4). Hence, the negatively correlated noise components are more intense in the worse quality lasers comparing with the good quality reliable devices. In our previous work [9] it is shown that negatively correlated optical and electrical fluctuations are observed due to leakage current through defects in the interfaces with active region, i. e. the negative cross-correlation factor, low quality and reliability of LDs are related with the leakage currents through the defects: the more intense leakage current causes both the smaller current through the active layer and the smaller radiation light power. Different defects that have formed leakage current channels redistribute the flowing current between a flow through the active region and a flow through the current blocking (in BH devices) or cladding layers. This current redistribution leads to the negatively correlated optical and electrical fluctuations in laser diode: the laser diode terminal voltage and optical output power fluctuate in opposite phases. On the other hand, the leakage current deteriorates LD operation characteristics and (due to the thermal effects) stimulates the device degradation [11, 12]. The defects in which the emission and capture of charge carriers randomly modulate the total current cause the positive cross-correlation function: the laser diode terminal voltage and light output power fluctuate in phase.

Laser diode optical and electrical noise spectra at stable operation range are of $1/f$ type [10]. But some samples over the threshold demonstrate additional negatively correlated white noise component (Fig. 5). The white noise component is related with the dot recombination centres having the same recombination energy level and a small relaxation time. These centres also create an additional leakage current and cause the negative cross-correlation factor between the electrical and optical fluctuations. On the other hand, these centres also worsen the reliability of lasers.

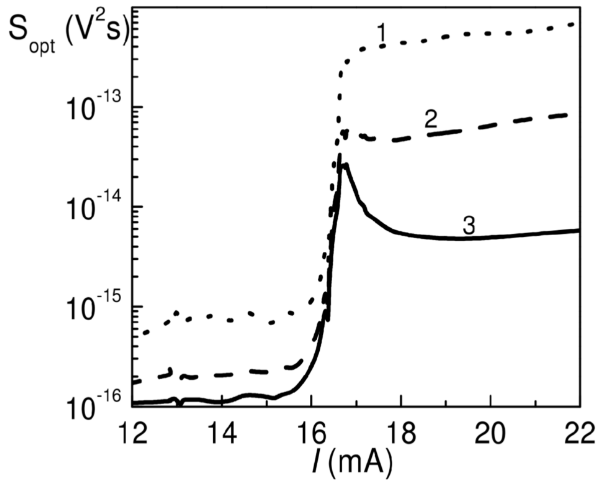
The threshold current region is the most sensitive to the various device structure imperfections because the operation at this region has a transitional unstable character. As it is impossible to make an ideal laser diode structure, its multiple-quantum-well active region contains particular ununiformities (especially in the case of distributed feedback laser, having refractive grating), the lasing conditions (the needed threshold carrier density) can not be satisfied in the whole active area at the same lowest threshold current: sub-areas are formed in the active region where lasing starts, and in other ones the threshold condition is not reached yet. At such transitional operation conditions the influence of defects is very strong. Only at a moderately larger current the lasing involves the whole active region.

4. Conclusions

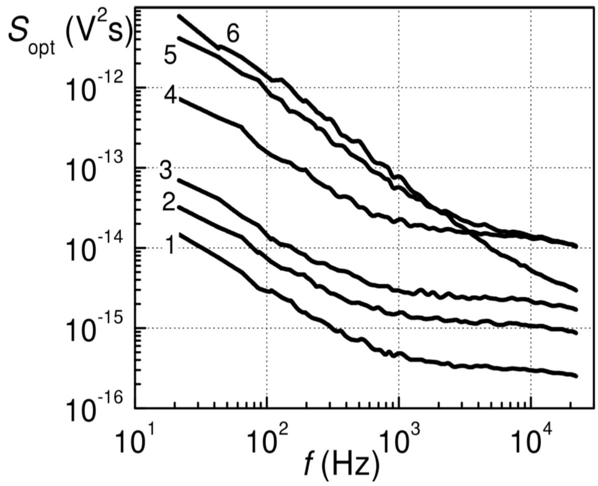
Comprehensive investigation of cross-correlation factor between optical and electrical noises of InGaAsP multiple-quantum-well laser diodes (LDs) has been carried out in the threshold current region.

It is shown that using correlation method and statistical averaging for laser diode optical noise measurements enables one to investigate the signals that are much lower than the measurement system noise, i. e. the optical noise measurement sensitivity is increased by about two orders of magnitude.

It is shown that worse laser quality and low reliability is due to leakage currents that cause negatively correlated optical and electrical fluctuations. This is especially evident in analyzing LD noise characteristics at the threshold. The found cross-correlation factor features related with laser diode reliability are common for laser diodes of various design: buried heterostructure and ridge waveguide, Fabry–Perot, and distributed feedback InGaAsP / InP multiple-quantum-well lasers.



(a)



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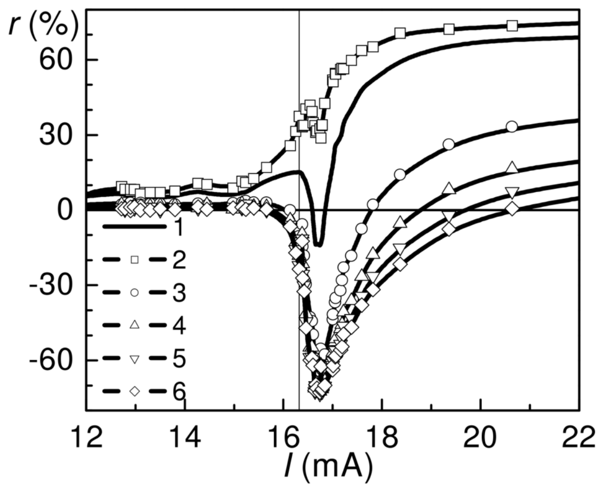

(c)

Fig. 5. Optical noise spectral density dependence on (a) laser current: *1* at 215 Hz, *2* at 1.05 kHz, *3* at 10.3 kHz, (b) optical noise spectra: *1* at 16.14 mA, *2* at 16.32 mA, *3* at 16.42 mA, *4* at 16.60 mA, *5* at 17.00 mA, *6* at 20.64 mA, and (c) cross-correlation factor dependence on laser current: *1* at 20 Hz – 22 kHz, *2* at 20 Hz – 4.4 kHz, *3* at 4.4 kHz – 8.8 kHz, *4* at 8.8 kHz – 13.2 kHz, *5* at 13.2 kHz – 17.6 kHz, *6* at 17.6 kHz – 22.0 kHz (sample: DFB RWG LD).

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InGaAsP / InP LAZERINIŲ DIODŲ TRIUKŠMŲ TYRIMAS SLENKSTINĖS SROVĖS SRITYJE

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Santrauka

Išsamiai ištirtos InGaAsP / InP lazerinių diodų (LD) su daugeliu kvantinių duobių aktyviojoje srityje triukšmų charakteristikos slenkstinės srovės srityje. LD veika slenkstinės srovės srityje yra nenuostovi, todėl slenksčio sritis yra labai jautri LD sandaros ypatybėms, darinyje esantiems defektams, kurie lemia lazerinio diodo kokybę ir patikimumą. Siekta nustatyti lazerinių diodų triukšmų charakteristikas priešslenkstinėje, slenksčio ir poslenkstinėje srityse, išsiaiškinti triukšmų charakteristikų ypatybių ryšį su tiriamųjų lazerinių diodų kokybe ir patikimumu.

Lazerinių diodų optinio triukšmo signalas priešslenkstinėje srityje yra labai silpnas, todėl jo neįmanoma išmatuoti įprastais triukšmų tyrimų metodais. Optinio triukšmo tyrimui priešslenkstinėje srityje pritaikius koreliacinį metodą ir statistinį vidurkinimą, matavimų sistemos jautrį pavyko padidinti maždaug dviem eilėmis.

Lazerinių diodų, kurių veikos charakteristikos (spinduliuotės galia, slenkstinė srovė) yra prastesnės ir linkusios sparčiai blogėti, abipusės koreliacijos koeficientas tarp optinių ir elektrinių fliktuacijų po slenksčio sparčiai mažėja nuo teigiamų verčių ((30–70)%) iki neigiamų. Neigiamas koreliacijos koeficientas tarp optinių ir elektrinių fliuktuacijų yra būdingas nuotėkio srovėms. Defektai, lemiantys nuotėkio sroves, taip pat mažina lazerinių diodų kokybę bei spartina charakteristikų blogėjimą. Ištirtos triukšmų charakteristikų ypatybės, susijusios su LD kokybe ir patikimumu, yra būdingos visiems tirtiems InGaAsP / InP lazerinių diodams (LD) su daugeliu kvantinių duobių ir nepriklauso nuo jų tipo (Fabri ir Pero bei lazeriai su paskirstytu grįžtamuoju ryšiu, lazeriai su keteriniu bangolaidžiu ir paslėptuoju įvairiatarpiu dariniu).