Low Frequency Noise Characteristics of Multimode and Singlemode Laser Diodes

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1. Introduction

Three main fluctuating quantities are considered in the laser diode (LD) noise investigation: emitted optical power (optical noise), phase (or frequency) and LD terminal voltage (electrical noise). Both phase and amplitude fluctuations of LD affect the performance of optical communication system. Phase fluctuations determine the linewidth, which is related with radiation frequency and is very important parameter (Jacobsen, 2010; Tsuchida, 2011). Amplitude fluctuations appear in both total output power and the output levels of longitudinal modes, and may indeed contribute significantly to the error rate for externally modulated LD operating at high data rate in communication system (Jacobsen, 2010; Nilson et al., 1991). The low frequency noise can beat with the modulation signal to produce enhanced noise in the "wings" around the modulation signal and causes significant degradation in signal-to-noise (S/N) performance in optical transmission (Gray & Agrawal, 1991; Lau et al., 1993). Electrical noise governs injected carrier number in the active region and therefore emitted photon number: optical and electrical fluctuations are partly correlated.

Intensity noise arises from a variety of sources, including gain fluctuations, spontaneous emission fluctuations, and relaxation oscillations (Fronen & Vandamme, 1988). At low frequencies both the optical and electrical fluctuations of LDs usually are of $1/f^{\alpha}$-type over all operation conditions (Fronen & Vandamme, 1988; Matukas et al., 1998, 2001; Orsal et al., 1994; Smetona et al., 2001; Tsuchida, 2011), noise intensity strongly depends on the defect density and their distribution within the active region of the laser. In (Jacobsen, 2010; Tsuchida, 2011), it was shown, that linewidth of the semiconductor laser strongly depends on the level of $1/f^{\alpha}$-type noise. In (Mohammadi & Pavlidis, 2000; Palenskis, 1990; Van der Ziel, 1970), it is shown that only the superposition of generation-recombination processes through the recombination centres in macroscopic defects with a wide relaxation time distribution can explain the $1/f^{\alpha}$-type noise spectra occurring over a wide frequency range. In (Orsal et al., 1994; Simmons & Sobiestianskas, 2005), there were shown, that low-frequency terminal electrical noise is highly correlated to the optical noise and that the electrical noise measurement could be used for *in situ* noise characterization of laser diodes without any optics and accompanying elements. But this conclusion is true only in the case, when the low frequency electrical noise is caused only by the defects in the active region of the laser. Noise characteristic investigation can clear up the reasons of various effects observed in the semiconductor laser operation.

The level of the noise is a measure of an uncertainty in the system and increases if there are more individual sources of defectiveness. If a given individual source changes its condition, so, that its effect on the system is less predictable, the noise level also increases. It is normal practice to assume that a noisy device will be less reliable and to reject it for any special application, where long life is an advantage (Amstrong & Smith, 1965; Jones, 2002; Lin Ke et al., 2010; Vandamme, 1994). Long-haul high-capacity optical communication systems require high performance and reliability components. Improvement of new and modern design LD structures requires detailed investigation of their operation characteristics. However, in reviewed works the noise characterization in semiconductor lasers is often presented just as complementary information. It is difficult to find papers devoted to the detailed noise characteristic feature investigations for various design modern semiconductor lasers. Understanding the origin of noise in the device could help improving the design and fabrication methods of LD, controlling noise level, selection of reliable devices. This Chapter overviews the low frequency noise characteristics of electrical and optical fluctuations, and their cross-correlation characteristics for different modern design multiple quantum well InGaAsP/InP laser diodes (LDs): Fabry-Pérot (FP) and distributed feedback (DFB), ridge-waveguide (index-guiding) and buried-heterostructure (gain–guiding) lasers. Great attention is paid to the mode-hopping effect in Fabry-Pérot laser operation. Also laser diode quality and reliability problems, their revealing via noise characteristics investigation are discussed.

2. Measurement methods of low frequency noise characteristic of laser diode

2.1 Experimental circuit for low-frequency noise measurement

In optoelectronic device noise characteristic investigation both optical (laser output power fluctuations) and electrical (laser diode terminal voltage fluctuations) noise signals are a point of interest, also cross-correlation factor between optical and electrical fluctuations gives valuable information on processes that take place in device structure. Therefore, measurements of optical and electrical signals have to be performed simultaneously, and cross-correlation must be evaluated.

In Fig. 1, there is presented measurement circuit for two noise sources investigation: optical and electrical. Laser diode emitted light and its power fluctuations are detected by photodiode that is suitable for radiation detection around 1.5 μm and 1.3 μm wavelength. Therefore, optical noise corresponds to the photodiode voltage fluctuation due to LD output power fluctuation; electrical noise – LD terminal voltage fluctuation. Current generator mode is guaranteed for LD by choosing appropriate feeding voltage and load resistance.

Optical and electrical noise measurements are performed simultaneously, i. e. processing of both noise signals is produced using two identical channels (Fig. 1), what enables calculation of cross-correlation between two noise signals. Noise signals are amplified by low-noise amplifiers, and then enter to analogue-to-digital converter (ADC) and PC. National Instrument™ PCI 6115 board (for measurements up to 1 MHz) or standard soundboard (for measurements in 20 Hz – 20 kHz frequency range) can be used as ADC. Noise characteristic measurements are performed both over the low frequency region (10 Hz – 100 kHz) and also in one-octave frequency band by using digital filters, having the following central frequencies f_c (Hz): 15, 30, 60, 120, 240, 480, 960, 1920, 3840, 7680, 15360, 30720, 61440, and 122880.

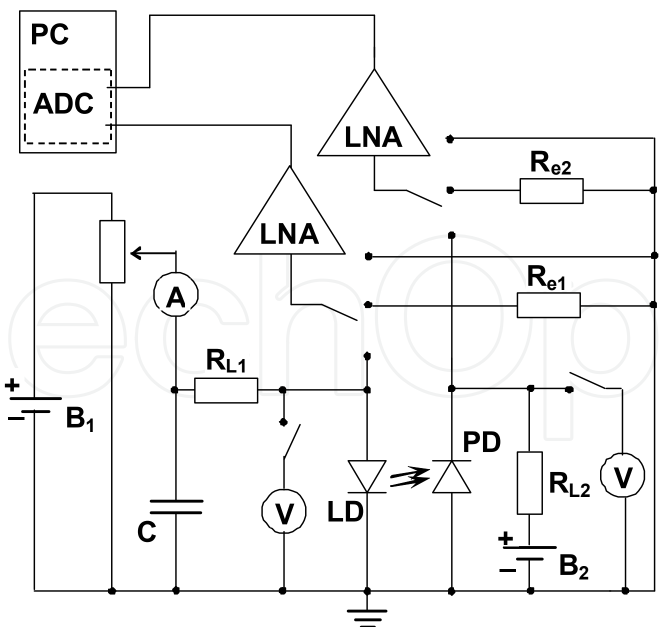

Fig. 1. Experiment circuit: LD – laser diode, PD – photodetector, R_{L1}, R_{L2} –load resistances, R_{e1}, R_{e2} – standard resistors, B_1 and B_2 – storage batteries, LNA – low-noise amplifier, ADC – analogue-to-digital converter, PC – personal computer.

Noise characteristic investigation is highly informative, quick and undestructive. However, noise signals usually are very low. Consequently, measurement system with low-noise components is needed. The most critical part of the low-frequency low-noise measurement system is the preamplifier, which usually establishes the sensitivity of the entire system. For the LD measurements special designed low-noise amplifiers (LNA in Fig. 1) with noise equivalent resistance of 90 Ω (at 1 kHz) are used. Carefully selected batteries, which exhibit low level of $1/f$ -type noise are used for measurements. The sample cell is protected from ambient electromagnetic fields by permalloy screen; the laboratory room is screened with copper and iron screens.

Laser diode radiation spectrum also can be measured together with noise characteristics. At the output the laser light beam is coupled into two fibres optical cable. One fibre is connected to the optical noise measurement equipment and the second - to the optical spectrum analyser „Advantest Q8384“. Optical spectrum of the LDs is measured with 10 fm accuracy.

2.2 Evaluation of noise signal spectral density and cross-correlation factor

Noise signals acquisition was performed by PC using Cooley-Tukey Fast Furrier transformation (FFT) algorithm. The calculated FFT spectral density results were averaged by using the large number (over 400) of sets (realizations) and by using frequency weight functions. An averaging according sets gives better accuracy at low-frequencies. Averaging by using frequency weight function does away with inaccuracy at high frequencies caused by FFT algorithm.

The noise spectral density, S_V, was evaluated by comparing with the thermal noise of the reference resistor R_e:

$$S_V = \frac{\overline{V_\mathrm{D}^2} - \overline{V_\mathrm{s}^2}}{\overline{V_\mathrm{e}^2} - \overline{V_\mathrm{s}^2}} 4kT_0R_\mathrm{e}\ [\mathrm{V}^2\mathrm{s}]; \quad (1)$$

where $\overline{V_\mathrm{D}^2}$, $\overline{V_\mathrm{s}^2}$ and $\overline{V_\mathrm{e}^2}$ are respectively the photodiode or laser, the measuring system, and the reference resistor thermal noise variances in the narrow frequency band Δf; T_0 is the absolute temperature of the reference resistor. The signal-to-noise ratio (S/N) was calculated as the ratio of output power (that is measured as photodiode load resistance voltage) and square root value from the optical fluctuation spectral density at a specified frequency. The simultaneous cross-correlation factor was expressed as

$$r = \frac{\overline{{}^1\!/\!_N \sum_{i=1}^{N} V_i^\mathrm{el} V_i^\mathrm{opt}}}{\sqrt{{}^1\!/\!_N \sum_{i=1}^{N} \left(V_i^\mathrm{el}\right)^2} \sqrt{{}^1\!/\!_N \sum_{i=1}^{N} \left(V_i^\mathrm{opt}\right)^2}} \cdot 100\%; \quad (2)$$

where $\sqrt{{}^1\!/\!_N \sum_{i=1}^{N} \left(V_i^\mathrm{el}\right)^2}$ and $\sqrt{{}^1\!/\!_N \sum_{i=1}^{N} \left(V_i^\mathrm{opt}\right)^2}$ are the root-mean-square values of noise signals V^el and V^opt that respectively correspond to the terminal voltage fluctuations of the laser diode and the photodetector voltage fluctuations due to laser light output power fluctuations at the same time. This formula allows obtaining not only the magnitude of cross-correlation factor between two signals, but also the correlation sign. As a positive correlation factor is taken a case, when a small increase of laser current creates an increase of both the laser terminal voltage and the light intensity; and negative correlation expresses situation, when one signal increases and the second decreases. The error of the evaluation of cross-correlation factor is less than 1 %.

3. Low frequency noise characteristics of multi-quantum-well laser diodes

In this Section, there are overviewed typical low frequency noise characteristics of singlemode distributed feedback (DFB) and multimode Fabry-Pérot (FP) laser diodes (Matukas et al., 1998, 2001; Palenskis et al., 2003, 2006; Pralgauskaite et al., 2004b). The presented results are for LDs with multiple quantum well (MQW) active region: different devices containing from 4 to 10 compressively strained quantum wells have been investigated.

Laser diodes at stable operation above the threshold current mainly distinguish by $1/f^\alpha$-type optical and electrical fluctuations (Figs. 2 and 3). This type of noise is characteristic for the many semiconductor devices (Jones, 1994; Mohammadi & Pavlidis, 2000; Palenskis, 1990; Vandamme, 1994; Van der Ziel, 1970;). Origin of it in semiconductor devices usually is superposition of many charge carriers generation-recombination (GR) processes through GR and capture centres with widely distributed relaxation times (Jones, 1994; Palenskis, 1990). These GR and capture centres are formed by various defects, dislocations and imperfections in the device structure. In optical fluctuations shot noise with white spectrum prevails $1/f^{\alpha}$-type fluctuations at higher frequencies (above 10 kHz). Optical shot noise is caused by the random photon emission process.

Positive cross-correlation ((10-60) %) is characteristic for $1/f^{\alpha}$-optical and electrical noise at the lasing (i. d. above threshold) operation (Fig. 3). $1/f^{\alpha}$-type noise in LDs is caused by the inherent material defects and defects created during the device formation. Resistance of the barrier (of the multiple-quantum-well structure) and adjacent to the active region layers fluctuation leads to the charge carrier number in the active region changes and therefore photon number fluctuation, and cause positively correlated optical and electrical $1/f^{\alpha}$-type noise. Thus, at the lasing operation there are active some defects, that randomly modulate the free charge carrier number in the active layer and, as a consequence, lead to the photon number fluctuations that have the same phase as the charge carrier number fluctuations. Optical and electrical noises are not 100 % correlated because part of the flowing current fluctuations is related with the regions remote from the active one (such as cap and substrate or passive layers). Remote region resistance fluctuations do not influence directly the charge carrier number in the active region, and, thus, do not affect the fluctuations of the photon number.

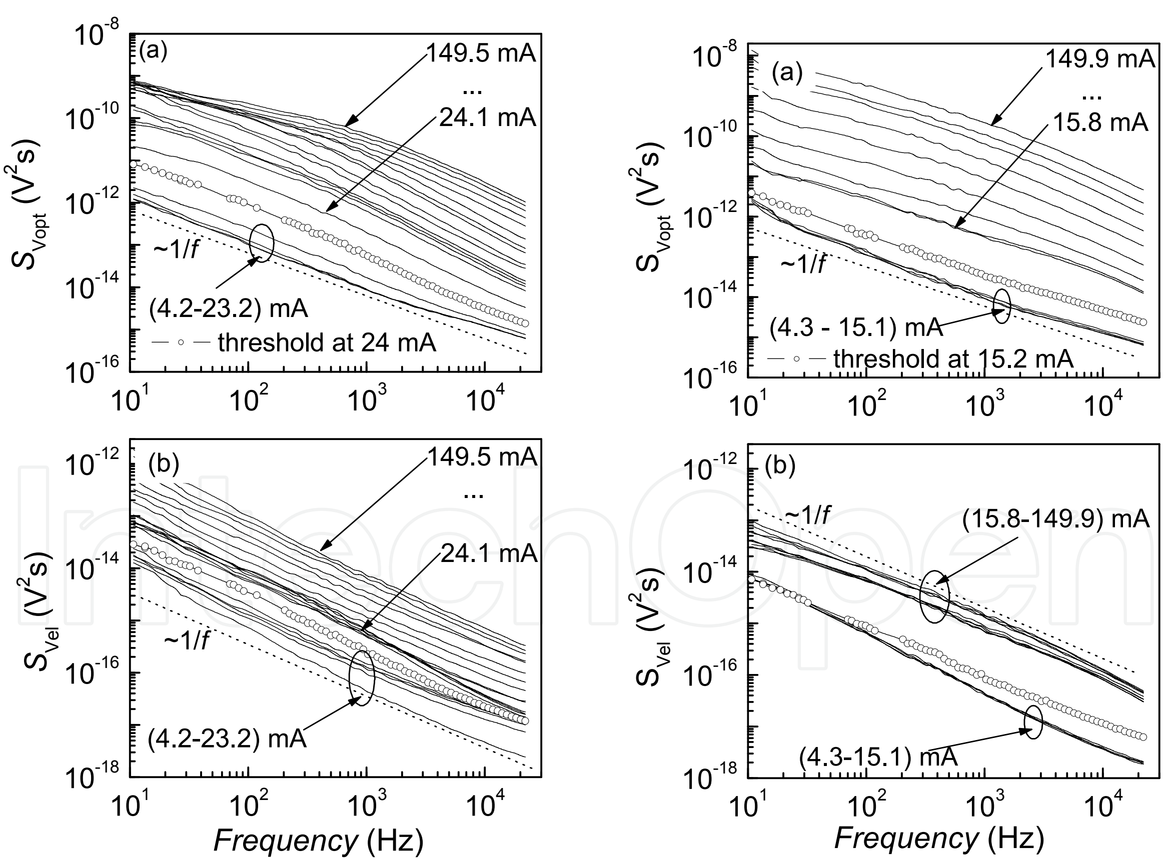

Fig. 2. Optical (a) and electrical (b) noise spectra for FP (on the left, at current ranges where there is no mode hopping) and DFB (on the right) lasers.

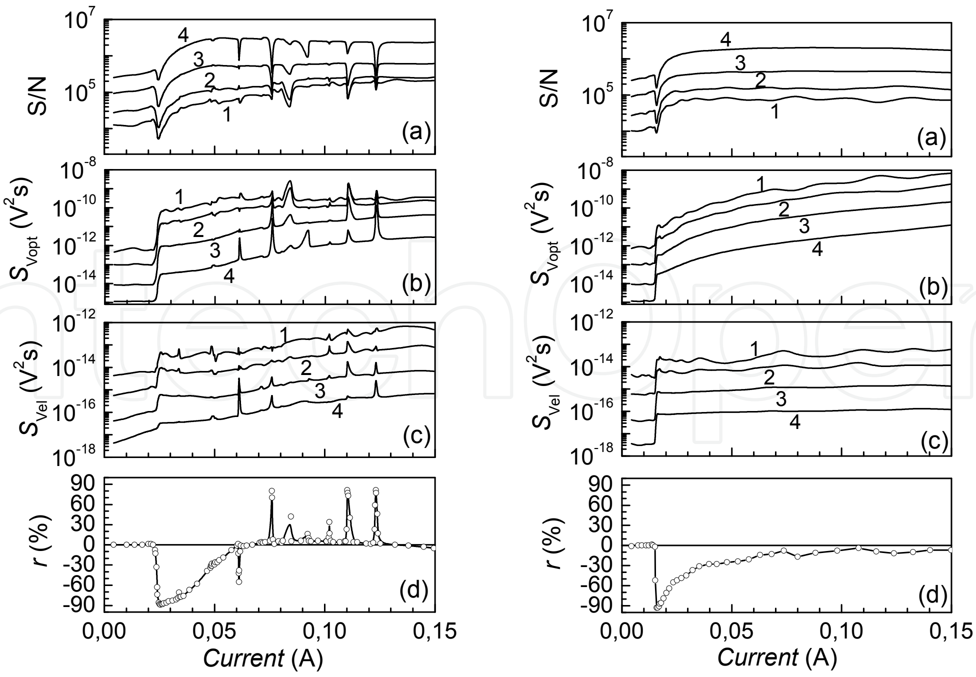

Fig. 3. Signal-to-noise ratio (a), optical (b) and electrical (c) noise spectral density (1- 22 Hz, 2- 108 Hz, 3-1 kHz, 4- 10 kHz), and cross-correlation factor between optical and electrical fluctuations (d; 20 Hz-20 kHz) dependencies on laser current for FP (on the left) and DFB (on the right) lasers.

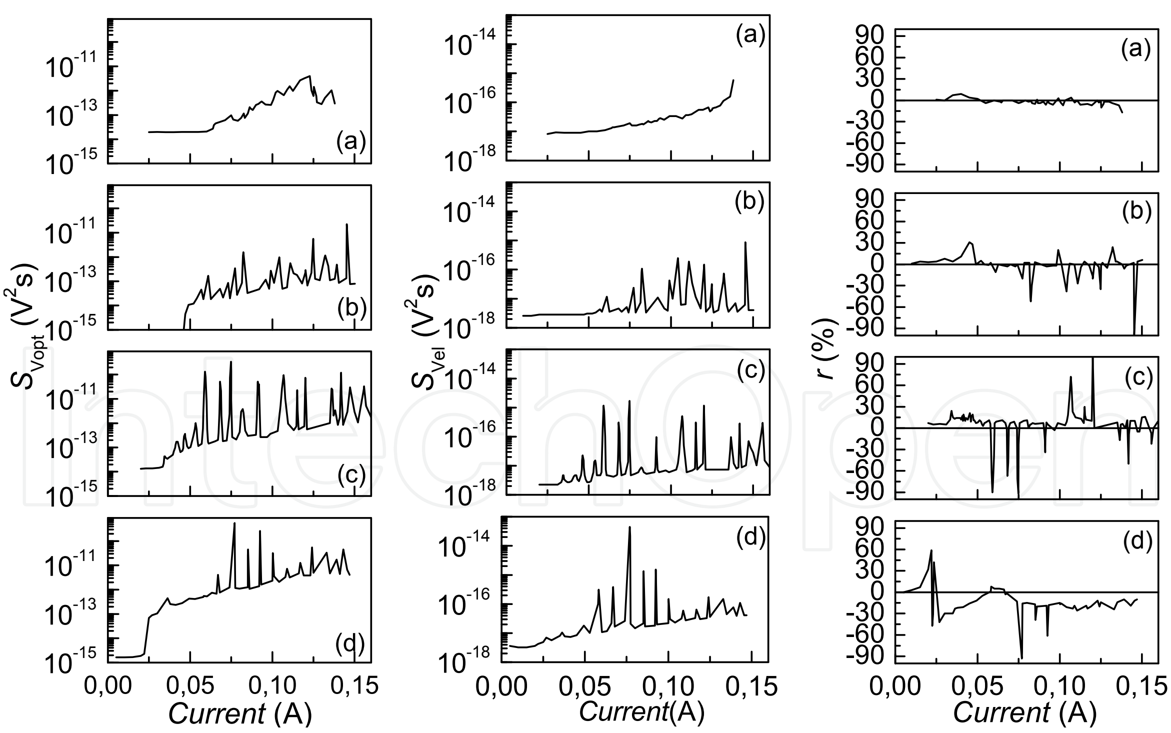

Fig. 4. Optical (on the left) and electrical (in the middle) noise spectral density (10 kHz), and cross-correlation factor between optical and electrical fluctuation (on the right, 1 Hz-1 kHz) dependencies on laser current for different cavity length FP lasers, having barrier layer energy bandgap E_g^b =1.08 eV: a) 1000 µm, b) 750 µm, c) 500 µm, d) 250 µm.

Fabry-Pérot laser noise characteristics at particular temperature and direct current values distinguish by large intensity highly correlated optical and electrical noise peaks (Fig. 3). These noise peaks are caused by the mode-hopping effect that is discussed in the next section. A batch of Fabry-Pérot lasers with some design differences (LDs with different cavity length ((250-1000) μm) and different barrier layer band-gap ((1.03-1.24) eV) has been investigated in order to find out how, these disparities reflect in LDs operation and noise characteristics. There are no clear differences in the noise characteristics of different structure laser diodes (Figs. 4 and 5) (Palenskis et al., 2003). Except long lasers (with cavity longer than 750 μm) that have worse characteristics (Fig. 4): lower efficiency, larger low frequency noise. Laser diodes with larger threshold current usually distinguish by worse other operation characteristics, too (Palenskis et al., 2003; Vurgafman & Meyer, 1997). Larger threshold current is related with more defective LD structure, what leads to the charge carrier leakage out of the active region: some defects randomly redistribute injected current between current component directly related with stimulated recombination and component associated with other processes (leakage current, non-radiative recombination) and lead to the more intensive $1/f^{\alpha}$-type optical and electrical fluctuations. Due to fabrication problems long laser structures contain more defects.

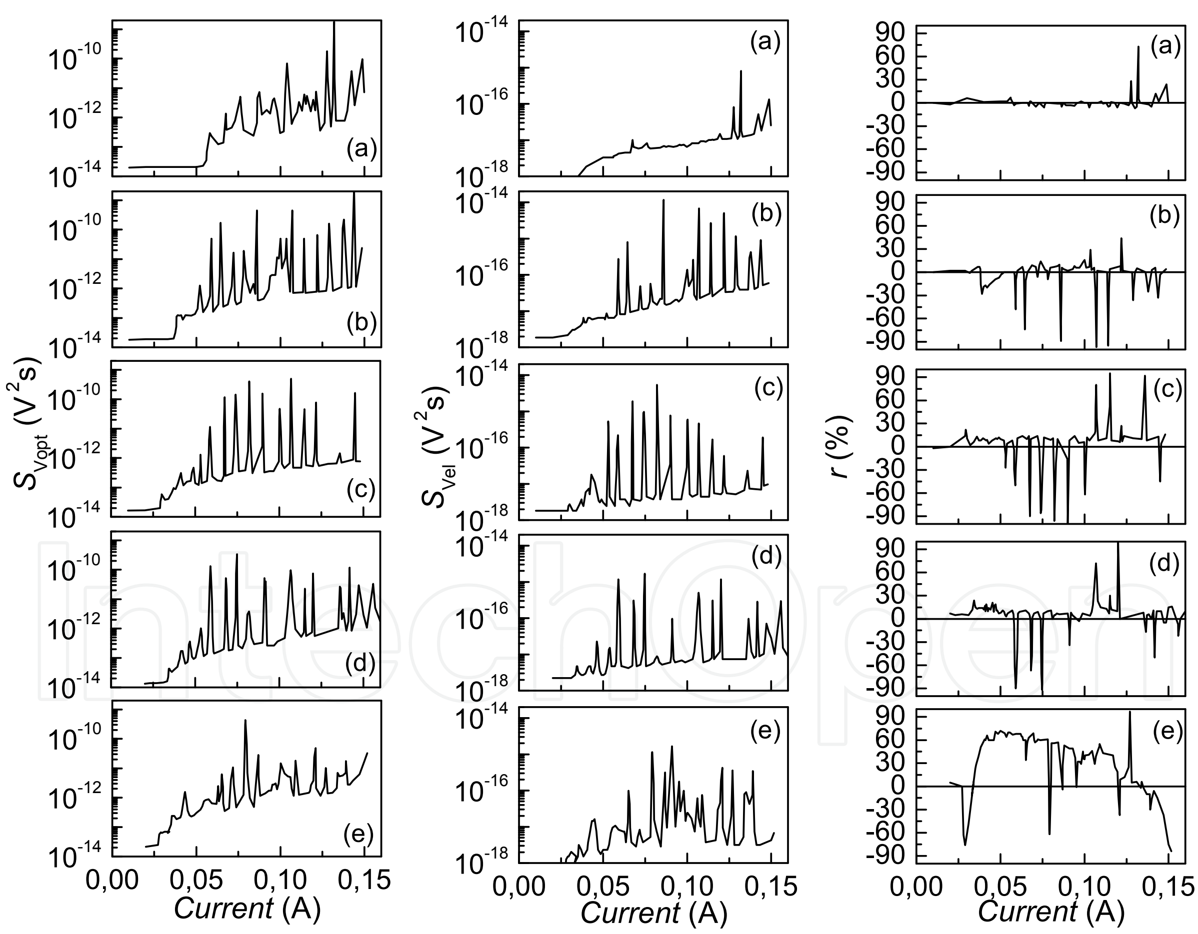

Fig. 5. Optical (on the left) and electrical (in the middle) noise spectral density (10 kHz), and cross-correlation factor between optical and electrical fluctuations (on the right; 1 Hz-1 kHz) dependencies on laser current of FP lasers with cavity length of 500 μm and different barrier layer energy band-gap: a) 1.24 eV, b) 1.18 eV, c) 1.13 eV, d) 1.08 eV, e) 1.03 eV.

In summary, optical and electrical fluctuations of semiconductor lasers at low frequency are $1/f^{\alpha}$-type noise caused by generation-recombination processes through the various defects and imperfections formed generation-recombination centres.

4. Mode-hopping effect in Fabry-Pérot laser diode operation

This Section presents discussion on noise characteristics of Fabry-Pérot lasers during mode-hopping effect, description of physical processes that take place during mode-hopping (Palenskis et al., 2003; Pralgauskaite et al., 2004b, 2011; Saulys et al., 2010).

Increase in the data communication worldwide requires the development of high-speed optical networks. As the number of channel in wavelength division multiplexing system increases and the channel spacing decreases, the requirements for the source wavelength accuracy become increasingly stringent. Multichannel dense wavelength division multiplexing systems require LDs with low-chirp and weak mode competition characteristics (Wilson, 2002). However when temperature varies the mode-hopping occurs in LD operation. Mode-hopping is an abrupt switching from one longitudinal mode to another: the lasing mode hops to another mode in single mode operation (SMO) or the peak mode changes in nearly SMO (Fig. 6), when the current and/or temperature changes, or due to back-reflection influence (Fukuda, 2000; Gity et al. 2006; Paoli, 1975). Mode-hopping noise of LD has been established to be one of the most limiting factors in high-speed lightwave systems. It causes redistribution of light intensity between longitudinal modes (Asaad et al., 2004; Orsal et al., 1994), and leads to an intensive fluctuation of intensity of output light power, to the wider and unstable LD radiation spectrum. During mode-hopping very intensive optical and electrical fluctuations with Lorentzian type spectrum are observed in the Fabry-Pérot laser operation (Figs. 3-5) (Palenskis et al., 2003; Pralgauskaite et al., 2011; Saulys et al., 2010). A detailed investigation of the low frequency noise characteristic of InGaAsP/InP Fabry-Pérot lasers with ten 4 nm thick compressively strained quantum wells in the active region was carried out in order to clear up the reasons of the mode-hopping and describe physical processes that lead to the very intensive optical and electrical noises, and high cross-correlation during mode-hopping.

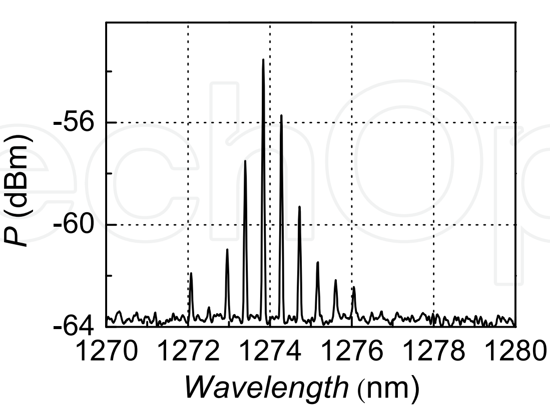

Fig. 6. Light emission spectrum of Fabry-Pérot LD at stable operation (at 72 mA forward current).

Mode-hoping, that took place in FP laser diode operation at particular operation conditions (at particular injection current and temperature), leads to the highly correlated intensive optical and electrical fluctuations (Fig. 7 and 8). Mode-hopping noise peaks are very

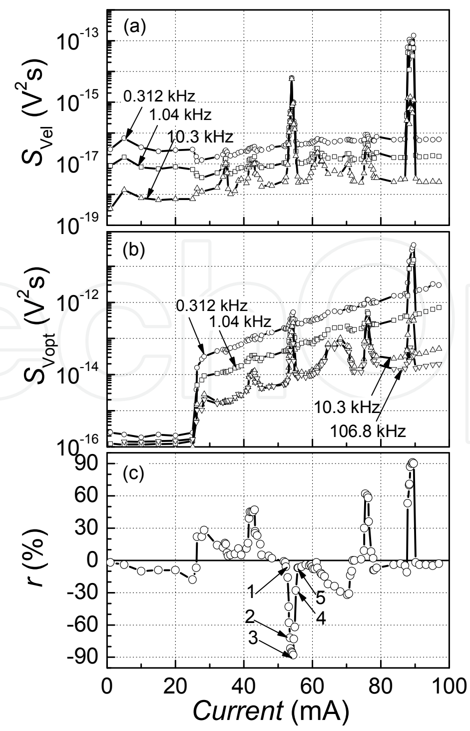

Fig. 7. Spectral density of electrical (a) and optical (b) noises at different frequencies and cross-correlation factor over 10 Hz – 20 kHz frequency range dependencies on injection current (FP laser with 500 µm cavity and 1.03 eV barrier layer band-gap).

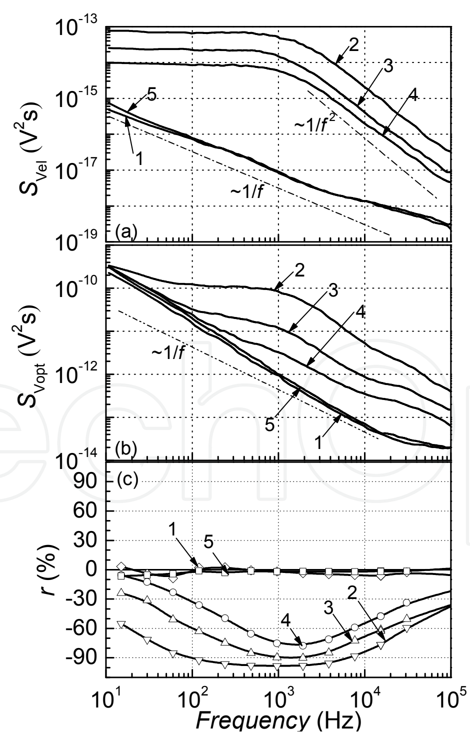

Fig. 8. Electrical (a) and optical (b) noise spectra and cross-correlation factor dependencies on frequency (c) at different injection currents (see numbered points in graph (c) in Fig. 7: 1- 52.1 mA, 2- 53.5 mA, 3- 54.4 mA, 4- 55.2 mA, 5- 55.9 mA) at mode- hopping region (FP laser with 500 µm cavity and 1.03 eV barrier layer band-gap).

sensitive to the laser current and temperature. Noise spectral density at mode-hopping is 1-3 orders of magnitude larger comparing to the stable operation region. Cross-correlation factor between optical and electrical fluctuations at mode-hopping increases up to (60-90) % and could be positive or negative. These correlated noise components distinguish by Lorentzian-type spectrum, and these fluctuations prevail $1/f^{\alpha}$ -type noise at the mode-hopping; also it is seen that high correlation appears only during mode-hopping and is close to zero over all frequency range during stable operation (Fig. 8). As it has been mentioned, optical and electrical noises at some mode-hopping peaks distinguish by positive and at others by negative cross-correlation. It was also observed that not in all peaks the optical and electrical noises are strongly correlated: in some cases correlation factor is small - (10-15) %. Lorentzian type noise at these peaks is weak, too. Different noise characteristics at the mode-hopping show that noise peaks are caused by separate noise sources, i. e. each noise peak may have a different origin. Also noise characteristics (the most evident is cross-correlation factor change) can change, when temperature changes (Fig. 9). Mode-hopping effect is extremely sensitive to the operation conditions: injection current and temperature, and occurs just in particular injection current and temperature ranges – out step of this range mode-hopping (and with it related intensive correlated Lorentzian type optical and electrical fluctuations) vanishes. When temperature increases, the noise peak position shifts to the lower current. The mode hopping position on temperature and current scales changes from sample to sample even for essentially identical devices. As it is shown in Fig. 9, cross-correlation peak related with mode-hopping is negative in particular range of the temperature and injection current, and it becomes positive, when temperature decreases further. This result again shows that there are more than one noise source in a sample related with intensive Lorentzian type noise.

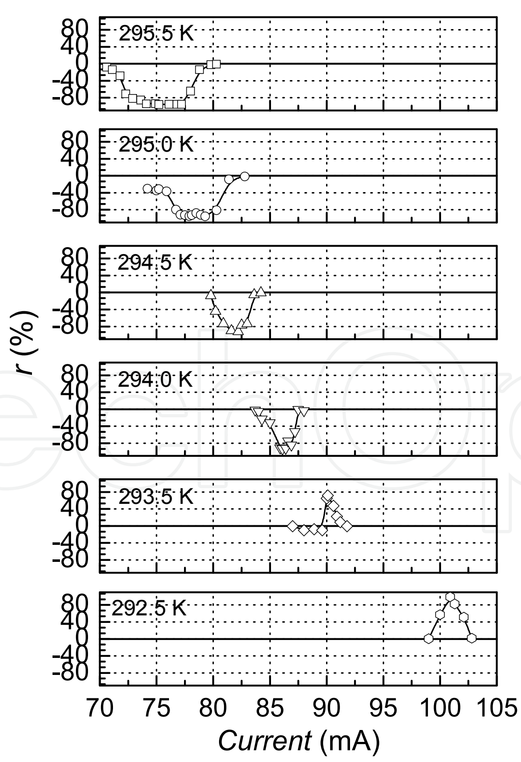

Fig. 9. Cross-correlation factor over 10 Hz – 20 kHz frequency range dependency on injection current at mode-hopping region at different temperatures (500 µm cavity length FP laser with 1.03 eV barrier layer band-gap).

Semiconductor laser radiation spectrum strongly depends on temperature, injection current and optical feedback. For the FP lasers at all laser operation conditions radiation of a few (3-5) longitudinal modes take place (Fig. 6). The main (the most intensive) radiating mode wavelength dependency on laser current is shown in Fig. 10. Laser diode optical gain spectrum moves evenly to the longer wavelength due to Joule heating (lines in Fig. 10) that increases with injection current and temperature increasing. But there are clearly seen uneven changes of the main mode wavelength, when laser current increases: at defined operation conditions these mode intensity redistributions occur in a random manner. Mode-hopping occurs, when laser diode optical gain spectrum (that maximum is determined by the quantum well band-gap energy) moves to the longer wavelength and gain of the adjacent mode exceeds the gain of the radiant peak mode. In this way, the peak longitudinal mode of the laser radiant spectrum changes to the next one (at longer wavelength side). However, there is particular temperature and injection current region, where both peak modes are radiated – laser radiation spectrum is randomly jumping between two radiant modes sets (Fig. 11) – mode-hopping occurs. And observed Lorentzian noise peaks occur during this random modes-hopping.

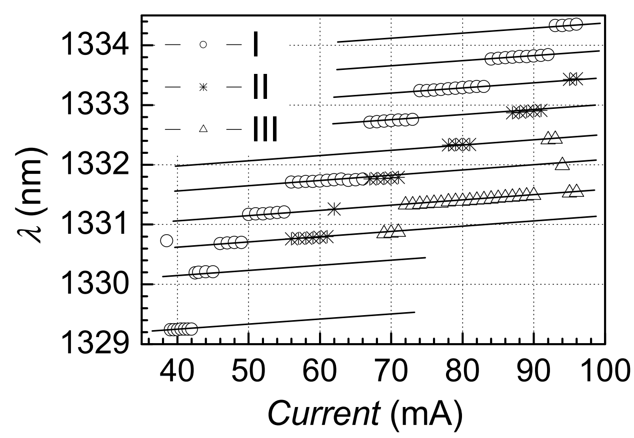

Fig. 10. Three the most intensive modes (I – the most intensive mode, II – the second, and III – the third mode) wavelength dependencies on the laser current at room temperature (FP laser with 500 μm cavity and 1.08 eV barrier layer band-gap).

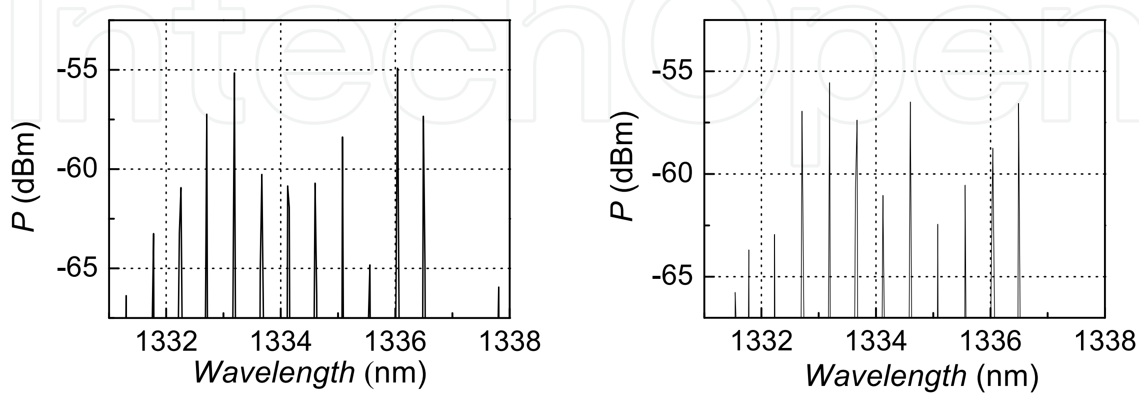

Fig. 11. LD radiation spectra at the mode-hopping operation at differrent time moments (at the same operation conditions: 294.5 K, 81.2 mA) (500 μm cavity length sample with 1.03 eV barrier layer bandgap).

Radiation spectrum of FP lasers is not stable during mode-hopping: optical gain randomly redistributes between several longitudinal mode sets. Consequently, laser diode operation at mode-hopping is unstable. Radiation spectrum of investigated FP LDs consists of two groups of longitudinal modes (in the case presented in Fig. 11 these two groups are around 1333 nm and 1336 nm). At the stable operation one of these groups is clearly more intensive comparing to the second one and total radiation spectrum consists from 5-7 longitudinal modes. When mode-hopping occurs the radiation spectrum visibly outspreads: both modes' groups are intensive, modes' intensity randomly changes in time and spectrum consists of 9-11 modes of almost equal intensity (Fig. 11).

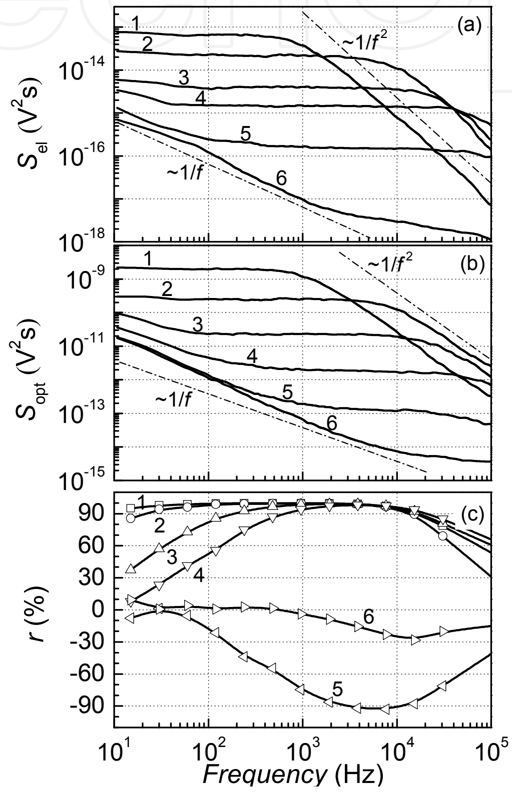

Fig. 12. Electrical (a) and optical (b) noise spectra and cross-correlation factor dependency on frequency at different injection currents and temperatures (1- 95.0 mA, 289.5 K; 2- 82.0 mA; 290.4 K; 3- 72.0 mA, 292.1 K; 4- 64.6 mA, 293.0 K; 5- 52.0 mA, 294.4 K; 6- 49.1 mA, 294.9 K) at the mode-hopping peak maximum (500 μm cavity length sample with 1.03 eV barrier layer band-gap).

Intensive fluctuations observed at mode-hopping peak distinguish by Lorentzian type spectrum and high cross-correlation between optical and electrical noises (Fig. 12). Cross-correlation measurements in one-octave frequency band show that correlation between optical and electrical fluctuations at the mode-hopping depends on frequency region (graph (c) in Fig. 12): the highest cross-correlation factor is found at the frequencies close to the cut-off frequency ($f_c=1/2\pi\tau$, here τ is the relaxation time) observed in noise spectra. When temperature is fixed, the cut-off frequency f_c of the Lorentzian noise does not change at different currents for the same mode-hopping peak. But for different samples, also for the same LD at different operation conditions, different cut-off frequencies are observed: they are in the range from kilohertz to a few megahertz. The characteristic relaxation times for the mode-hopping Lorentzian type noise are distributed from a few milliseconds to a few microseconds (Figs. 12 and 13). The intensive noise during mode-hopping could be related to the recombination processes in the barrier layer that have different capture cross-sections for electrons and, thus, different relaxation times. This leads to different cut-off frequencies of Lorentzian type spectra during mode-hopping for the same sample. As there is large cross-correlation between optical and electrical fluctuations, it shows that these centres are located in the active region. But observed characteristic times indicate that these processes are not related with radiative and non-radiative recombination in the active region (characteristic time of these processes is in the range of nanoseconds). During mode-hopping fulfilment of longitudinal mode radiation threshold condition randomly changes between two mode sets. Injected charge carrier redistribution and lasing energy level position is governed randomly by the state of generation- recombination and carrier capture centres (these centres randomly modulate the barrier height, and therefore the position of lasing levels). Therefore there is strong cross-correlation between optical and electrical fluctuations during mode-hopping. Considering that radiative recombination of charge carriers can occur only in quantum wells, it can be stated that correlated electrical and light intensity fluctuations are related with the random potential height fluctuations of barrier layer due to charge carrier capture and recombination in defects of the barrier layers. These potential fluctuations modulate that part of the carriers that recombines in quantum wells and produce photons.

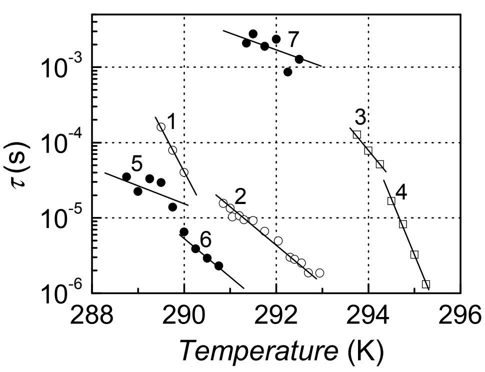

Fig. 13. Characteristic time dependencies on temperature for different Lorentzian noise peaks during mode-hopping for the 1.03 eV barrier layer band-gap sample with 500 µm cavity length (open symbols): 1- current range from 95.0 mA to 89.4 mA, 2- 82.0 mA – 64.6 mA, 3- 88.2 mA – 84.1 mA, 4- 81.9 mA – 75.6 mA; and for the laser with 1.18 eV barrier layer band-gap and 250 µm cavity length (solid symbols): 5- current range from 61.1 mA to 55.3 mA, 6- 55.3 mA – 52.3 mA, 7- 51.5 mA – 43.1 mA.

LD radiation spectrum and mode competition strongly depends on the laser resonator quality and back reflected light (Agrawal & Shen, 1986). Therefore influence of the laser facet reflectivity on the noise characteristics and mode-hopping effect has been investigated (Palenskis et al., 2003). Laser facet coating with thin polymer layer changes laser operation (Figs. 14 and 15). After coating (facet reflectivity decreases) LD threshold current slightly increases (from 46.8 mA to 51.0 mA) and efficiency decreases: the optical output power is reduced about 15 % (Fig. 14). In spite of the optical power losses, changes in the noise characteristics given advantages are more significant: after facet coating there are less mode-hopping noise peaks, and noise intensity at the remained peaks is lower about two orders of magnitude (Fig. 14). The mode hopping noise level after coating is substantially reduced, but the background ($1/f^{\alpha}$-type) optical noise level increases about two-three times, while the electrical one decreases by the same degree (Fig. 15). Such small $1/f^{\alpha}$-type noise intensity

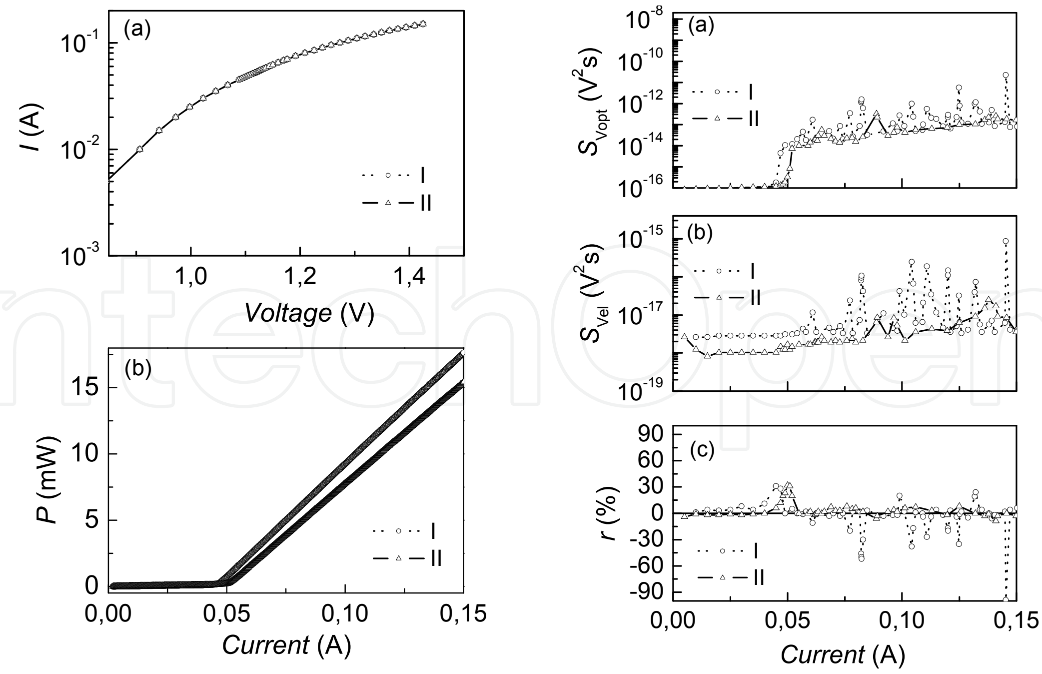

Fig. 14. Current-voltage (a) and LI (b) characteristics before (I) and after (II) antireflection coating (on the left); optical (a) and electrical (b) noise spectral density (10 kHz), and cross-correlation factor between optical and electrical fluctuations (c; 20 Hz-20 kHz) dependencies on laser current before (I) and after (II) antireflection coating (on the right) (FP laser with 750 μm cavity length and 1.08 eV barrier layer band-gap) (Smetona et al., 2001).

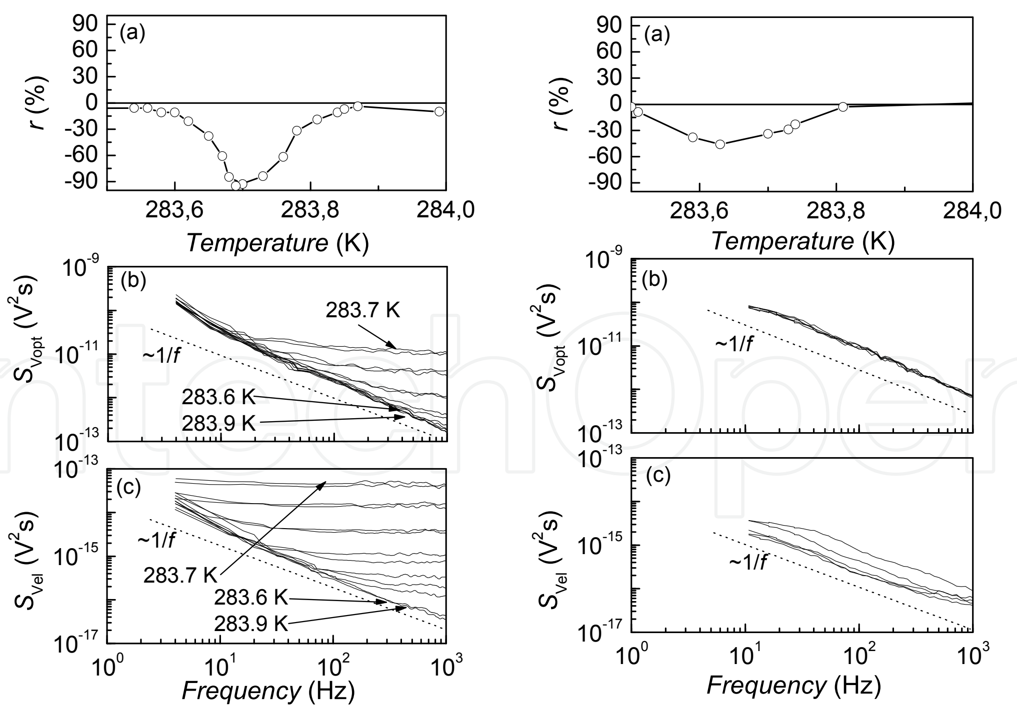

Fig. 15. Cross-correlation factor between optical and electrical fluctuations (a; 1 Hz-1 kHz), optical (b) and electrical (c) noise spectra at the mode-hopping peak before (on the left) and after (on the right) antireflection coating (FP laser with 500 μm cavity length and 1.08 eV barrier layer band-gap).

changes are not important. Lorentzian type noise related with mode-hopping almost disappears after coating: mode-hopping noise becomes lower the background $1/f^{\alpha}$-type noise. But cross-correlation factor still feels existence of the correlated noise related with mode-hopping (Fig. 15). So, cross-correlation is more sensitive to the various operation peculiarities.

Decreasing of the resonator mirror reflection leads to the decrease of the resonator quality, and to the significant reduction of the mode concurrency. Due to the same reasons current and temperature range, where mode hopping event occurs, become wider: weaker mode competition leads to the less strict transition between different radiation spectra. So, after the facet coating FP LD operation becomes more stable.

On the other hand, laser facets coating by antireflection layer results indicate that the level of back-reflected light is very important to the LD operation changing charge carrier and photon distribution and confinement in the active layer and neighbouring regions.

Summary of the Section. Noise characteristics at the mode-hopping point distinguish by highly correlated intensive Lorentzian type optical and electrical fluctuations - mode-hopping noise peaks. Mode-hopping occurs at particular operation conditions: position of these noise peaks is very sensitive to the current, temperature and optical feedback. The charge carrier lifetime in the active region of a few nanoseconds is much shorter than relaxation times of physical processes related with Lorentzian type noise during mode-hopping (that ranges from microseconds to millisecond). This indicates that mode-hopping is not related with charge carrier stimulated or spontaneous recombination in the quantum wells. Mode-hopping effect arises due to charge carrier gathering not in the quantum wells but in the barrier or cladding layers: generation-recombination and carrier capture processes in the centres formed by defects in the barrier and/or cladding layers (random change of state of the centres modulates barrier height and, therefore, lasing conditions for each longitudinal mode). Different cross-correlation factor value and sign, different Lorentzian type spectrum cut-off frequencies at different LD operation conditions show that there are several type recombination centres (with different capture cross-section) that determine FP LD noise characteristics during mode-hopping.

5. Noise characteristics and reliability of laser diodes

Reliability of the laser diodes is a key parameter in various applications, and its prediction in early phase of fabrication could significantly lower the expenses. Low-frequency $1/f^{\alpha}$-type noise is a typical excess noise that is a very sensitive measure of the quality and reliability of optoelectronic devices, as it is related with the defectiveness of the structure of the device (Jones, 2002; Lin Ke et al., 2010; Vandamme, 1994). Measurement of low frequency noise can indicate the presence of intrinsic defects as well as fabrication imperfections, which act as deep traps or recombination centres in semiconductor materials and their structures (Fukuda et al., 1993; Jones, 1994; Palenskis, 1990). This section presents noise characteristic analysis that was performed in order to clear up the origin of laser diode lower quality and degradation, factors that accelerate degradation, to find out noise parameter that could be used for LD quality and reliability prediction. For these purposes special attention was paid to the noise features at the threshold current, aging experiments and measurements at low bias have been carried out (Letal et al., 2002; Matukas et al., 2001; Palenskis et al., 2006; Pralgauskaite et al., 2003, 2004a, 2004b).

On purpose for set tasks specially selected few batches of MQW DFB lasers radiating around 1.55 μm wavelength have been investigated. Sample batches differ by the device reliability: the reliability of the devices was checked on the ground of the threshold current changes with aging time:

- lasers from the batch G are rapidly degrading devices;
- samples from the batch H distinguish by very good quality and reliability.

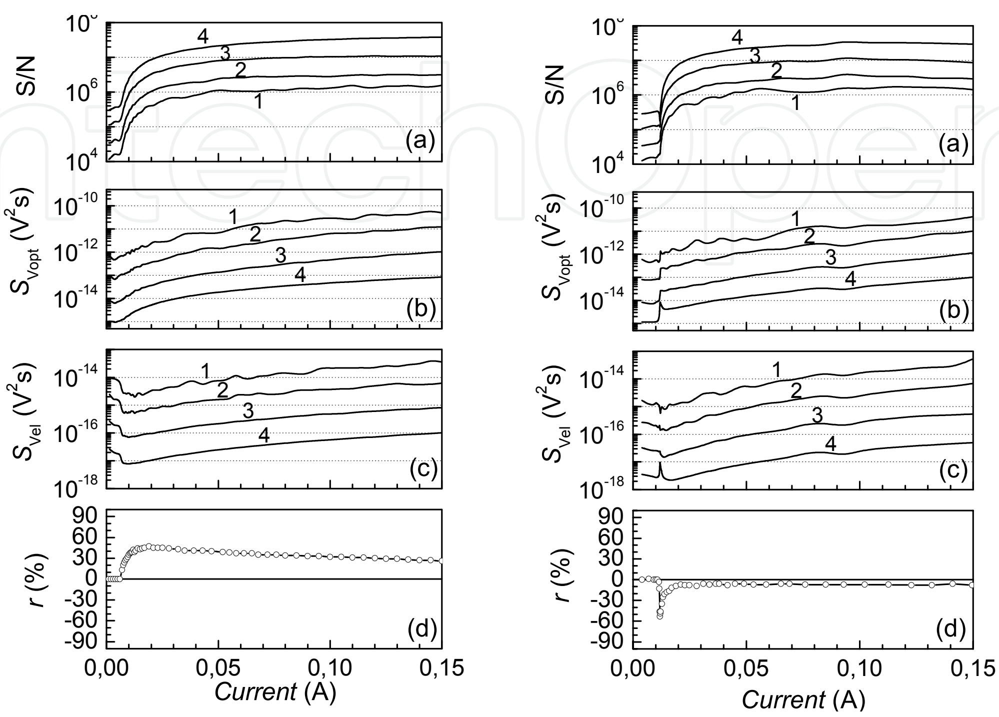

Fig. 16. Signal-to-noise ratio (a), optical (b) and electrical (c) noise spectral density (1- 22 Hz, 2- 108 Hz, 3- 1 kHz, 4- 10 kHz), and cross-correlation factor between optical and electrical fluctuations (d; 20 Hz-20 kHz) dependencies on laser current for reliable laser from batch H (on the left) and quickly degrading one from batch G (on the right) before aging. Reprinted with permission from (Letal et al., 2002). Copyright 2002, American Vacuum Society.

Primarily let us compare initial (of not aged samples) noise characteristics of LDs that would-be of different reliability (Fig. 16). The noise measurement results for stable and degrading not-aged LDs exhibited some differences in noise characteristic. The noise intensity in the lasing operation region of samples from all investigated batches is similar: the optical and electrical noise spectra are of $1/f^{\alpha}$ -type and noise intensity increases approximately proportionally to the laser current. But cross-correlation factor is more sensitive to the laser quality. It is able reflect operation differences that cannot be observed in noise spectral density level, because noise signal is a superposition of a lot of various noise origins and their intensities are averaged. Larger positive correlation at lasing current has been observed for better quality lasers (graphs (d) in Fig. 16): stable devices (batch H) exhibit strong positive cross-correlation factor ((30-60) % for different samples) between the electrical and optical noises above threshold, while rapidly degrading samples (batch G) distinguish by close to zero or even negative cross-correlation factor above threshold. Various semiconductor growth and laser processing defects cause $1/f^{\alpha}$-type noise. Positive correlation in the LD operation indicates that device contains defects in the barrier and other layers close to the active region that substantially modulate current flowing through the active region and lead to the charge carrier and photon number changes in-phase. The defects that cause positively correlated optical and electrical fluctuations distinguish by noise spectra of $1/f^{\alpha}$-type. Injection current fluctuations in the layers remote from the active region are the reason of not 100 % correlation between optical and electrical noises.

The cross-correlation factor behaviour of degrading lasers can be explained as the superposition of two noise sources, the second of which distinguishes by the negative cross-correlation. LD threshold current magnitude is related with laser diode quality: better quality samples usually have lower threshold. Influence on the cross-correlation of the negatively correlated noise components increases with sample threshold current increase. Noise source that causes optical and electrical noises with negative cross-correlation are originated from defects related with leakage current (therefore, larger threshold current is needed to achieve lasing). The existence of such defects is reflected in the cross-correlation between optical and electrical fluctuations.

Accelerated aging experiments have been applied for both groups of lasers: ~500 h aging at 100 ^{0}C and 150 mA forward current. Clear noise characteristic degradation of rapidly degrading samples G has been observed after aging (Fig. 17): after aging $1/f^{\alpha}$-type noise intensity of G samples increases about a half of order, while there are no noticeable changes in H LDs operation. Cross-correlation factor between G laser optical and electrical noise changes are especially evident: cross-correlation factor become negative (about 50 % (before aging it was close to zero)) over all lasing current range (graph (d) in Fig. 17). These operation changes during long-time aging indicate that in the G devices structure there are mobile defects that migrate during aging and cause operation characteristic degradation.

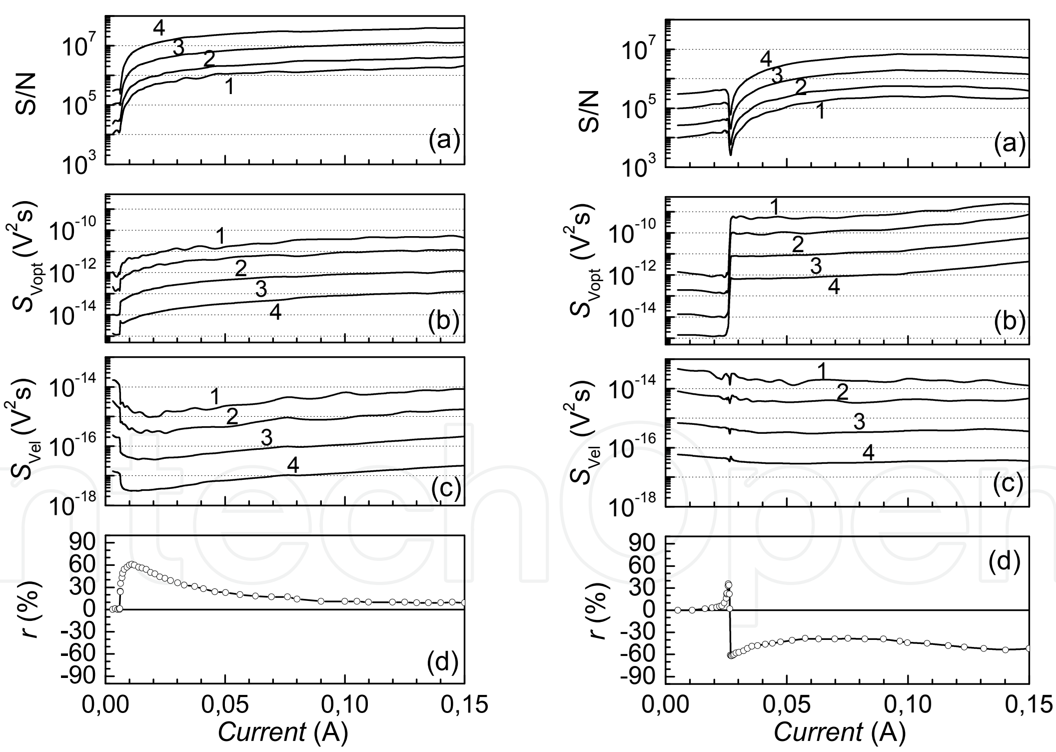

Fig. 17. Signal-to-noise ratio (a), optical (b) and electrical (c) noise spectral density (1- 22 Hz, 2- 108 Hz, 3- 1 kHz, 4- 10 kHz), and cross-correlation factor between optical and electrical fluctuations (d; 20 Hz-20 kHz) dependencies on laser current for reliable laser from batch H (on the left) and quickly degrading one from batch G (on the right) after aging (aging conditions: 100 ^{0}C, 150 mA, ~500 h). Reprinted with permission from (Letal et al., 2002). Copyright 2002, American Vacuum Society.

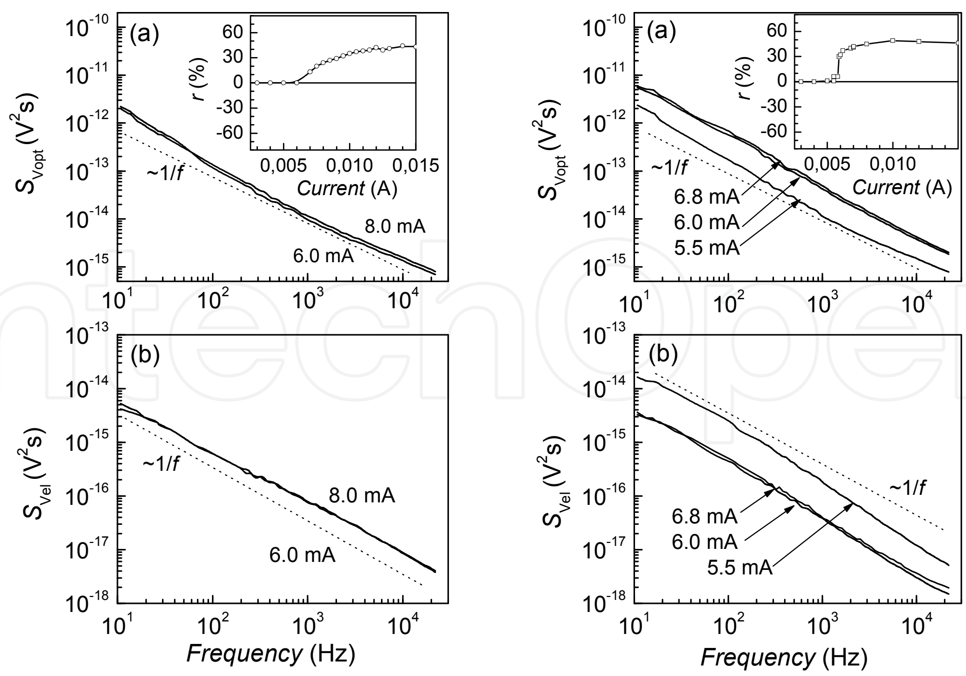

Fig. 18. Optical (a) and electrical (b) noise spectra for reliable laser from batch H around the threshold before (on the left) and after (on the right) aging (aging conditions: 100 ^{0}C, 150 mA, ~500 h; inset: cross-correlation factor dependency on laser current in frequency range 20 Hz-20 kHz). Reprinted with permission from (Letal et al., 2002). Copyright (2002), American Vacuum Society.

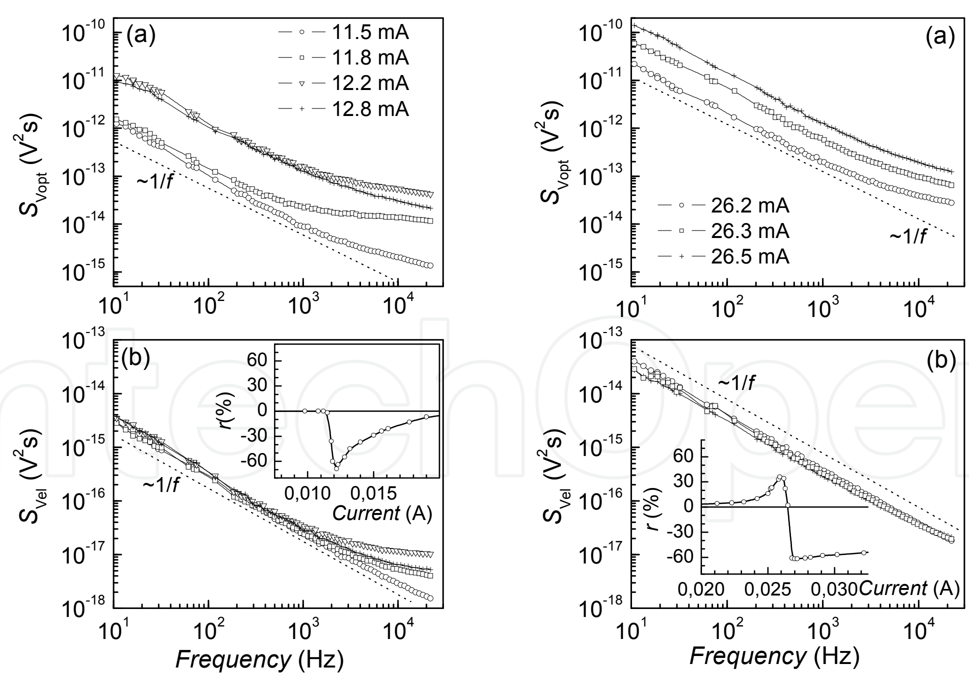

Fig. 19. Optical (a) and electrical (b) noise spectra for quickly degrading laser from batch G around the threshold before (on the left) and after (on the right) aging (aging conditions: 100 ^{0}C, 150 mA, ~500 h; inset: cross-correlation factor dependency on laser current in frequency range 20 Hz-20 kHz). Reprinted with permission from (Letal et al., 2002). Copyright 2002 American Vacuum Society.

Special attention was paid to the noise characteristics in the threshold region (Figs. 18 and 19), as it was found that this transitional operation region is especially sensitive to the device quality. Laser diode threshold characteristics are important due to the threshold parameters that cause the lasing action characteristics.

Lasers from the group G distinguish not only by the larger threshold current, but also by rapid it degradation during aging. Noise characteristics at the threshold after long-time aging have degraded, too. Both optical and electrical noise intensity at the threshold increases after aging by more than an order of magnitude, additional Lorentzian type noise with characteristic negative cross-correlation is observed at the threshold, and pulse noise appearance could be expected below threshold (Fig. 19). Threshold noise characteristics of the stable samples do not change during long-time aging (Fig. 18).

From Fig. 20, it is seen that negative cross-correlation at the threshold region is caused by the higher frequency fluctuation component. At lower frequencies (20 Hz-1 kHz), where $1/f^{\alpha}$-type noise intensity exceeds the Lorentzian type noise level (curve number 1 in Fig. 20) positive cross-correlation factor value is observed. This shows that electrical and optical fluctuations with $1/f^{\alpha}$ -type spectrum distinguish by the positive cross-correlation (from 10 % to 30 % for different samples). These results contrast with that, what is observed at the higher, 1 kHz-20 kHz, frequency range (curve number 4 in Fig. 20), where Lorentzian type noise component dominates in the low quality LD operation. The negative cross-correlation factor is observed at the threshold of the degrading sample before aging. Thus, Lorentzian type noise and negative cross-correlation observed at the threshold are caused by the same origin (i. e. additional "white" electrical and optical fluctuations are negatively correlated). $1/f^{\alpha}$-type and Lorentzian type noises superpose at the threshold current region.

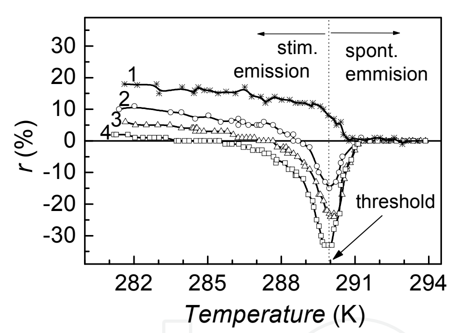

Fig. 20. Typical cross-correlation factor behaviour in the vicinity of the threshold region for the degrading sample: cross-correlation factor dependency on temperature at the threshold current (10.1 mA) (1: 20 Hz–1 kHz, 2: 20 Hz–20 kHz, 3: 200 Hz–20 kHz, 4: 1 kHz–20 kHz; the device was not aged). Reprinted with permission from (Letal et al., 2002). Copyright 2002 American Vacuum Society.

It is observed significant differences in noise characteristic in the vicinity of the threshold between good and poor quality LDs (Figs. 18 and 19). To relate noise characteristic features with LD reliability the detailed low temperature short-time aging experiments have been conducted: 60 ^{0}C temperature and forward current in the range of (100-150) mA have been chosen as aging conditions. Not-burned-in samples from good and poor LD quality groups H and G have been chosen for aging experiments. In Figs. 21 and 22, $I{\times}t$ parameter on x-axes (laser aging current multiplied by aging time) is used in order to avoid confusion due to different current used in different aging steps (at initial aging phase lower current was used because noise characteristic changes have occurred during extremely short time).

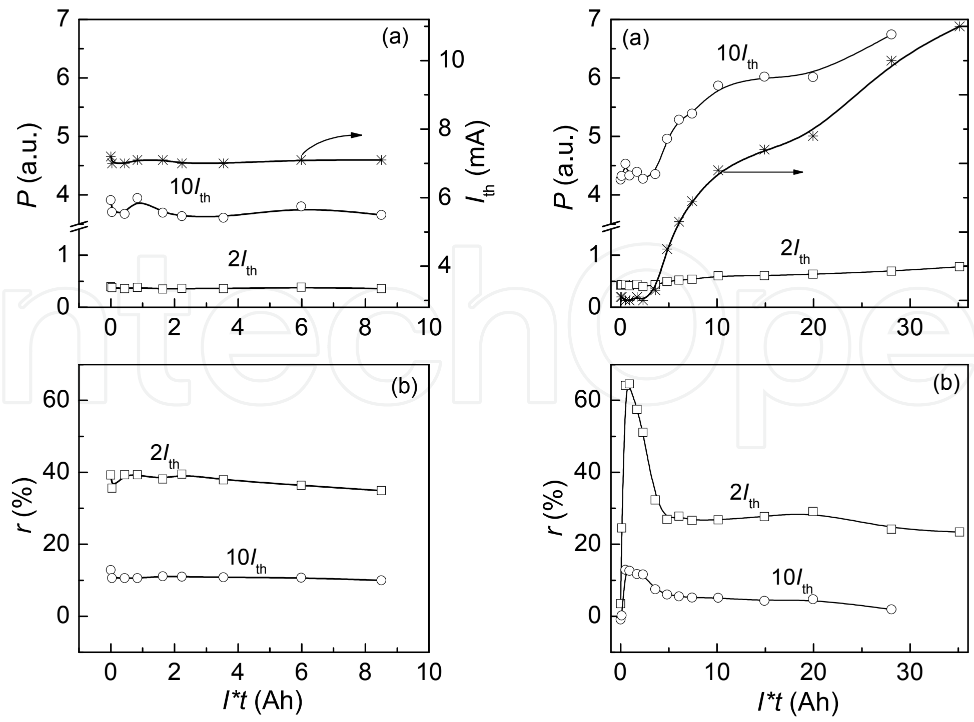

Fig. 21. Optical output power (a, *P*), threshold current (a, I_{th}) and cross-correlation factor (b; 20 Hz-20 kHz) dependencies on the aging time for different laser currents of reliable (on the left, batch H) and degrading (on the right, batch G) LDs (Pralgauskaite et al., 2004a).

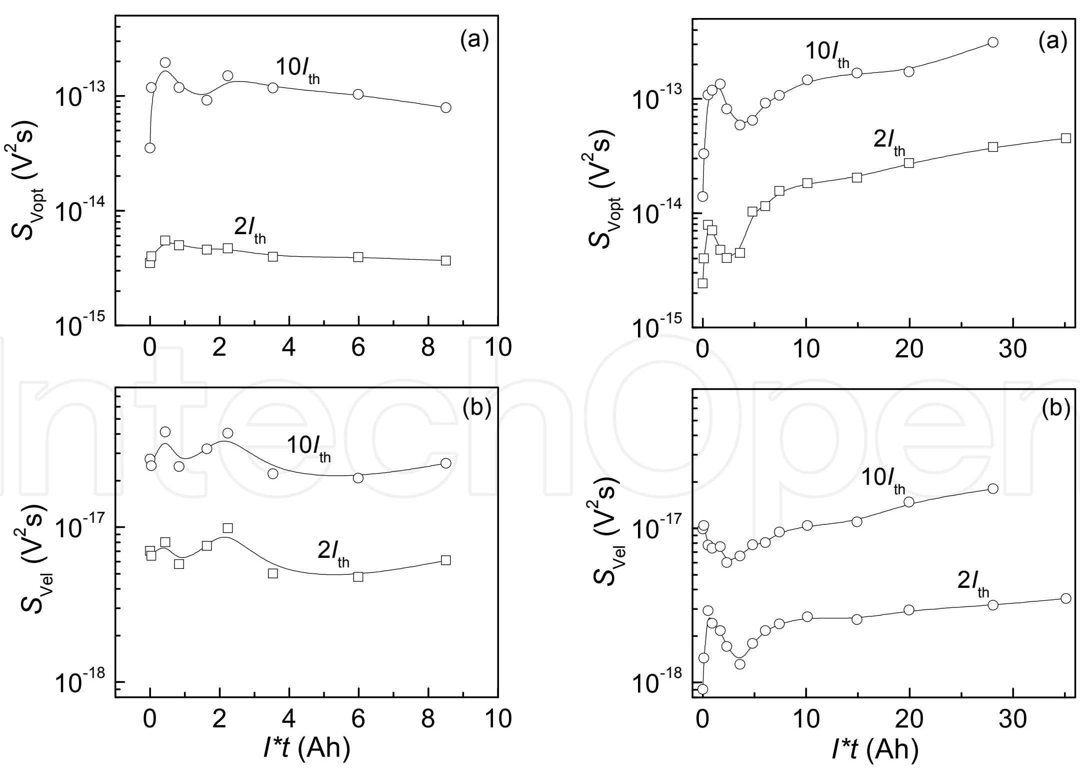

Fig. 22. Optical (a) and electrical (b) noise spectral density (10 kHz) dependencies on the aging time for different laser currents of reliable (on the left, batch H) and degrading (on the right, batch G) lasers (Pralgauskaite et al., 2004a).

Good quality stable devices from group H show neither threshold current and output power, nor noise intensity and cross-correlation factor changes during aging (Figs. 21 and 22). The results indicate that defects that cause $1/f^{\alpha}$-type noise with characteristic positive cross-correlation are stable and do not change their position and parameters during aging. Good quality lasers do not have mobile defects that cause Lorentzian type noise with characteristic negative cross-correlation at the threshold and that deteriorate LD operation characteristics during aging.

Threshold current and output power intensity of degrading devices from group G do not increase in the initial phase of the aging, while noise characteristic changes are the largest in this phase (Figs. 21 and 22). The largest changes have been observed in the cross-correlation between optical and electrical fluctuations factor: e. g., at forward current approximately equal to $2I_{th}$ cross-correlation factor changes from 0 to 68 % (graph (b) in Fig. 21). After further aging stage (next (6-8) h) cross-correlation factor decreases to more moderate positive value, while optical and electrical noise intensities stay at higher level and have tendency slightly increase with aging time. When threshold current of degrading device starts to increase with aging time ($I \times t$>4 Ah, graph (a) in Fig. 21), noise characteristic changes have saturated (Fig. 22). Therefore, noise characteristics are more sensitive to the processes related with short LD lifetime than threshold current or output power, and could let know beforehand about rapid device degradation.

To confirm that worse quality (large threshold current, short lifetime) of laser diodes is related with defects that cause current leakage out of the active region, investigations at low bias (at currents much lower the threshold one) have been carried out. Operation at low bias (<1 mA for investigated laser diodes) is very sensitive to the current flow conditions through the structure as at low current density, if structure is defective, current flows not through the whole device cross-section, but through the defects formed leakage channels (Jones, 2002; Shuang et al., 2007). Therefore this investigation can clear up the diode reliability problems. In Fig. 23, there are compared low bias characteristics of the same design but different quality devices. A non-ideality factor of current-voltage characteristic, *m*, for investigated samples for all groups is larger than 2 (the latter value is a characteristic one for good quality *pn* diodes), what indicates non-uniform current flow and leakage current: the larger value of non-ideality factor the larger leakage current is implied. It is clear seen that larger non-ideality factor is characteristic for samples with larger threshold current and worse reliability; good quality laser diodes from the H batch have much smaller leakage current compare to the degrading samples from the G batch (Fig. 23). Consequently, origin of poor lasing characteristics, worse reliability and leakage currents are related.

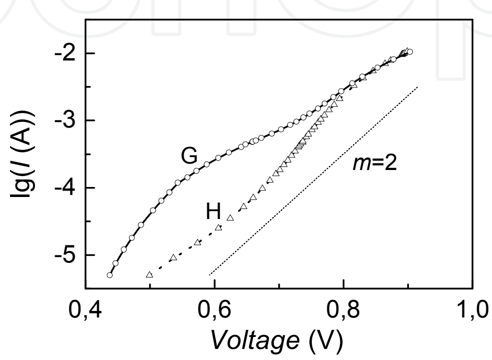

Fig. 23. Current-voltage characteristics for good (H) and worse (G) quality laser diodes.

Summarizing this Section, reasons of worse operation characteristics and poor reliability are common for various design semiconductor lasers: defects at the active region interface lead to the injected charge carrier leakage out of the active region. These defects increase leakage current that leads to the larger threshold current. Defects migrate during aging to form clusters that deteriorate laser characteristics. Low-frequency noise investigation, especially cross-correlation factor behaviour analysis at the threshold, can detect the presence of such defects in the laser diode structure.

6. Noise characteristics and reliability of buried heterostructure laser diodes

Buried-heterostructure (BH) laser diodes distinguish by extremely low threshold current and high efficiency. The advantages are achieved due to strict injection current and optical field confinement in the active region by the current-blocking layers (Lee et al., 2008; Mito et al., 1982; Nunoya et al., 2000; Yamazaki et al., 1999). But additional etching and current-blocking layers regrowth introduce defects at the interface between the active region and current-blocking layers (Fukuda et al., 1993; Krakowski et al., 1989; Oohashi et al., 1999). Such defects, in principle, can lead to the worse LD operation characteristics and quick degradation. It is possible for such lasers to exhibit thyristor turn-on, what does away with laser operation. For the proper LD operation the thyristor turn-on current has to be significantly higher than the operating one and does not reduce with aging. This Section is concentrated on buried-heterostructure laser quality problems (Letal et al., 2002; Matukas et al., 2002; Pralgauskaite et al., 2003).

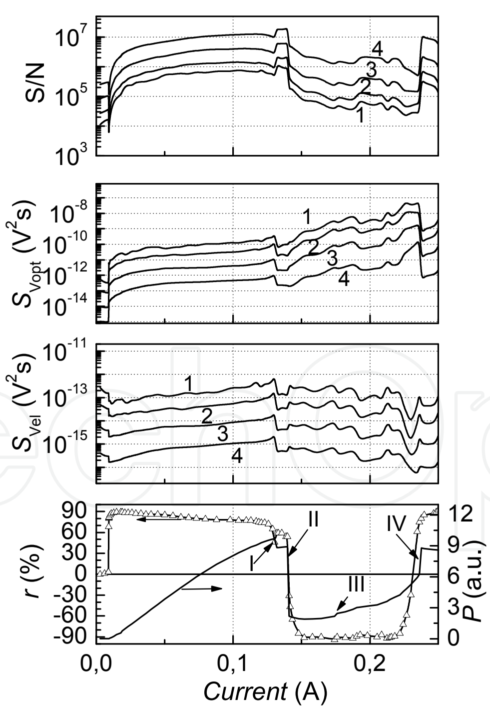

Fig. 24. Signal-to-noise ratio (S/N), optical (S_{vopt}) and electrical (S_{vel}) fluctuation spectral density (1 – 22 Hz, 2 – 108 Hz, 3 – 1.03 kHz, 4 – 10.7 kHz), cross-correlation factor (*r*; 20 Hz–20 kHz) and optical output power (*P*) dependencies on laser current of BH LD with thyristor-like forward breakdown. Reprinted with permission from (Letal et al., 2002). Copyright 2002 American Vacuum Society.

A set of BH DFB devices, where the thyristor turns-on at relatively low currents (~120 mA) due to a non-optimal current-blocking layer growth, has been investigated. The larger injection current, the larger leakage current flows through *pnpn* current-blocking layers. When the particular leakage current is reached the thyristor turns-on. In this regime the resistance of the blocking layers decreases, what causes a sudden decrease of the current density in the active region and the optical output power: the current-voltage and LI characteristics exhibit a kink (Fig. 24). The optical output power and signal-to-noise ratio are very low, when the thyristor has turned-on, and the optical noise is a complex function of the current (Fig. 24). Even so, the noise intensity remains at its characteristic values, and in some current regions is even higher. Cross-correlation factor at current higher than the thyristor turn-on also has a complex behaviour (Fig. 24). Noise characteristics of these samples at lower currents (below the thyristor turn-on current) are typical for the DFB laser diodes and do not have any peculiarities. Noise spectra are $1/f^{\alpha}$-type (graphs (a) in Fig. 25).

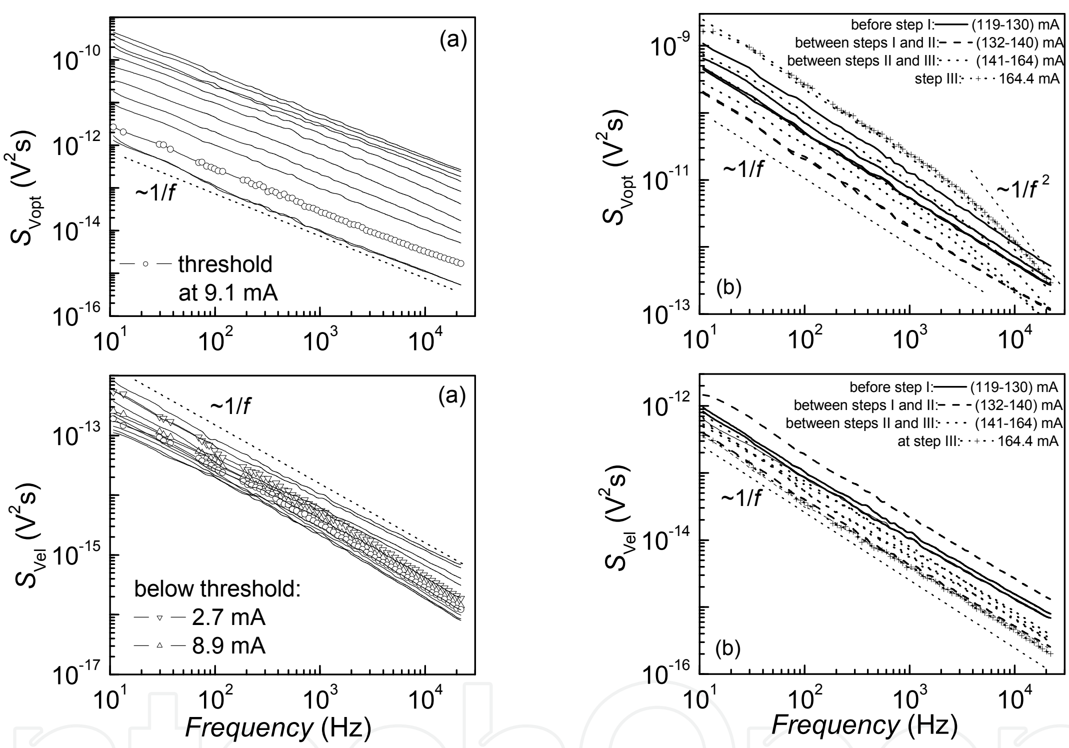

Fig. 25. Optical (S_{Vopt}) and electrical (S_{Vel}) noise spectra of BH laser diode with thyristor-like forward breakdown: (a) below thyristor turn-on current ((3-117) mA), (b) in the current range from 117 mA to 165 mA (for numerated steps look at Fig. 24).

For these samples at lasing operation very large (>90%) positive cross-correlation factor is characteristic (Fig. 24). In addition, optical and electrical noise spectral densities are about 1-2 order of magnitude larger (and the signal-to-noise ratio is about 3 times lower) in the normal lasing region for these devices comparing to the BH lasers without thyristor turn-on effect. These results suggest that in the “thyristor” case, the active region of the BH laser contains additional defects that causes non-uniform current flow and its leakage to the current-blocking layers, and affects both the electrical and optical noise. When coming close to the each kink in the LI characteristic optical and electrical noise intensities increase up to very large values. With sudden optical power decrease noise intensity decreases to the "normal" operation values, and cross-correlation factor changes from positive to negative (Fig. 24). For the low optical power region large negative cross-correlation factor is characteristic. At the "bottom", when optical power is low, optical noise intensity stays large enough, so, signal-to-noise ratio is very low. Cross-correlation factor becomes positive again if optical power increases. After the thyristor turns-on the Lorentzian type component with cut-of frequency of ≈3 kHz has been observed in the optical noise spectra (graphs (b)-(d) in Fig. 25). Therefore, some processes with characteristic time of 0.3 ms decide optical fluctuations. In Fig. 26, there are presented possible charge carrier leakage to the thyristor-type current-blocking layers paths. Current leakage through resistances R_L leads to the lowering of the thyristor forward breakdown voltage. So, accurate controlling of the active region position with respect to the blocking layers *np* junction has to be guaranteed.

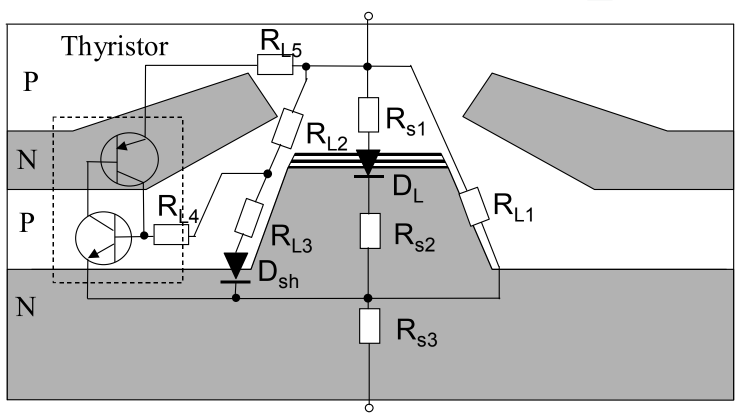

Fig. 26. Schematic diagram of BH LD structure showing leakage paths (R_L - leakage path resistances, R_s - series resistances, D_L is the laser diode, and D_{sh} is the shunt diode in the blocking layers). Reprinted with permission from (Letal et al., 2002). Copyright 2002 American Vacuum Society.

Summary of the Section. Formation of current-blocking layers in buried-heterostructure LDs structure introduces additional defects in the active region interface that lead to the injection current leakage out of the active region and enables thyristor turn-on at low current. Low frequency noise characteristics indicate larger density of defects at the active region interface of BH lasers: devices that exhibit a low-current thyristor turn-on show strongly correlated intensive $1/f^{\alpha}$ -type optical and electrical low-frequency noise both before and after the turn-on.

7. Conclusions

Semiconductor lasers at stable lasing operation distinguish by $1/f^{\alpha}$ -type partly correlated optical and electrical fluctuations that are caused by the inherent material defects and defects created during the device formation. Lorentzian type noise peaks observed during mode-hopping effect in Fabry-Pérot laser operation are related to the recombination processes in the barrier and cladding layers through the centers formed by the defects (random change of the state of the centers modulates barrier height and, therefore, lasing conditions for each longitudinal mode, that are very sensitive to the light reflection from the facets) involving electrons and holes having different capture cross-sections, what is reflected in different cut-off frequencies of the Lorentzian spectra.

Worse characteristics (larger threshold current, lower efficiency) and poor reliability of laser diodes are caused by the presence of defects at the surface of the active region. These defects increase the leakage currents that lead to the larger LDs threshold. Presence of such defects in LD structure manifests as additional negatively correlated Lorentzian type noise (especially evident at the threshold operation). During ageing, these defects migrate, form clusters, deteriorate the laser characteristics, and, ultimately, cause the failure of LD. Low-frequency noise investigations can detect the presence of these defects.

The presented data suggests that electrical and optical noise tests (especially cross-correlation factor investigation at the threshold), that are quick and undestructive, can be used as the lifetest screen to distinguish reliable and unreliable laser diodes without traditional long-time lifetime tests.

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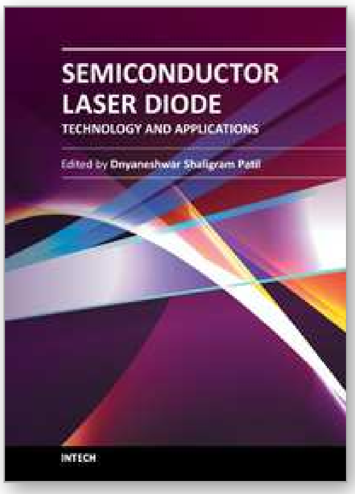

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This book represents a unique collection of the latest developments in the rapidly developing world of semiconductor laser diode technology and applications. An international group of distinguished contributors have covered particular aspects and the book includes optimization of semiconductor laser diode parameters for fascinating applications. This collection of chapters will be of considerable interest to engineers, scientists, technologists and physicists working in research and development in the field of semiconductor laser diode, as well as to young researchers who are at the beginning of their career.