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Investigation of InGaAsP/InP DFB and FP Laser Diodes Noise Characteristic

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In the paper, there are presented comprehensive noise characteristics (electrical and optical noise and correlation between electrical and optical fluctuations) investigations that were performed with the aim to clear up the reasons of short lifetime of laser diode (LD) and to find out LD design and fabrication features that can increase laser diode quality. Groups of different quality InGaAsP laser diodes have been investigated. Investigation has shown that Fabry-Perot (FP) laser facet coating with antireflection layer suppresses the mode hopping effect (that is characteristic for FP laser operation): LD facet coating reduces resonator quality and leads to the more stable laser operation. It is shown that noise characteristic features that indicate laser diode quality and reliability problems are the most significant at LD operation below and in the vicinity of the threshold region. These noise features are related to additional generation-recombination processes and current leakage out of the active region: some of the investigated laser structures have defects that lead to the leakage current, generation-recombination noise, worse operation characteristics and rapid device degradation.
Keywords: laser diode, noise, electrical noise, optical noise, correlation, quality, reliability, mode hopping.

1. INTRODUCTION

One of the widely used applications of InGaAsP laser diodes is high-speed optical communication networks, where all components should have excellent operation characteristics and long lifetime. The mean time of LD failure in telecommunication systems is required to be greater than 25 years for the terrestrial long-haul transmission systems and 300 years for the transoceanic submarine cable systems. An early device reliability prediction and removing the defective samples in the fabrication process could guarantee stable operation of whole system in future and minimize the service expenses. Traditional lifetime tests require sufficient large expenditures (time, temperature, and current), and usually are performed on relatively small number of samples by accelerating the failure processes by applying a high stress. These methods are inherently destructive and the results are statistical in nature.

Low-frequency noise characteristics are very sensitive to the various imperfections of material and device, such as defects, impurities, surface and interface states [1 – 7]. Usually the low-frequency noise is caused by the same type of defects that also reduce device quality and reliability. So, non-destructive low-frequency noise spectroscopy performed under normal bias conditions can be an indicator of failure mechanisms and can reveal in situ potentially "bad" devices whose lifetime is expected to be short [1, 2, 4 – 6]. The noise analysis provides useful information on the nature of the noise sources and points out on device design and fabrication failings.

In our earlier papers, it is presented wide study on the nature of mode hopping effect that is characteristic for Fabry-Perot laser operation [8], and it is shown that LD noise characteristics are very sensitive to their quality problems [9]. Here we present further and wider noise characteristic investigations with aim to look for the reasons of worse LD quality and technology features that influence semiconductor laser operation characteristics and reliability.

2. INVESTIGATED DEVICES

Different groups of the InGaAsP Fabry-Perot (FP) and distributed feedback (DFB) buried-heterostructure LDs with multiple-quantum-well active region have been used for the investigation. The radiation wavelength of the investigated devices is 1.55 μm. The FP and DFB lasers have been made from the same growth wafer by masking off a part of the wafer when the grating was etched.

Devices from different growth wafers (in the paper there are presented results for samples from two wafers referred as A and B) that differ in reliability have been investigated. Laser quality was tested by applying an accelerated ageing (at dc current 150 mA and temperature 100 ºC) and lifetime tests to a part of the devices. Lasers from the wafer A have shown operation characteristics changes during accelerated ageing, while operation characteristics of lasers from the wafer B were more stable. Light emission power vs. laser current characteristic analyses have shown that the same design lasers with moderately larger threshold current have higher efficiency due to small differences in the LD structure that leads to the larger threshold charge carrier density. On the other hand, it was noticed that samples with very large threshold current have extremely low efficiency: in this case large carrier leakage through the diode passive regions take place. This stands for the threshold current changes during ageing, too. Large threshold current and rapid its degradation for the devices from the wafer A as compared to the wafer B are related to more defective structure of the LDs from the wafer A.

3. MEASUREMENT RESULTS AND DISCUSSION

Optical (LD output power fluctuations detected as photodiode voltage fluctuations) and electrical (LD terminal voltage fluctuations) noise signals were measured simultaneously, value and sign of the correlation factor

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between these fluctuations were evaluated using unique noise measurement technique [9].

3.1. Facets coating influence on the Fabry-Perot LD operation

Fabry-Perot laser diode operation distinguishes by the mode hopping effect: the semiconductor laser radiation spectrum strongly depends on temperature, injection current and optical feedback, so, at defined operation conditions radiating mode set is changed salutatory: random mode

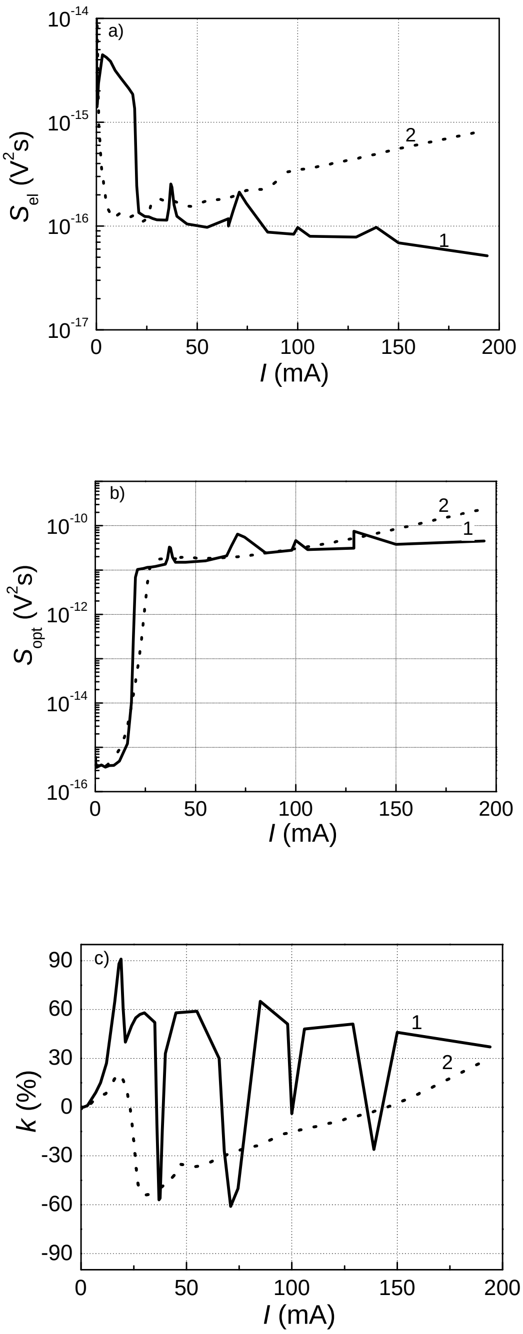

Fig. 1. Low-frequency noise characteristics of the FP lasers: a – electrical and b – optical fluctuation spectral density at 1.03 kHz, and c – correlation factor between optical and electrical noise signals in the frequency range 10 Hz – 20 kHz dependencies on laser current: sample A03 without facet coating (curve 1 – solid line), and sample B02 with facet coating (curve 2 – dot line)

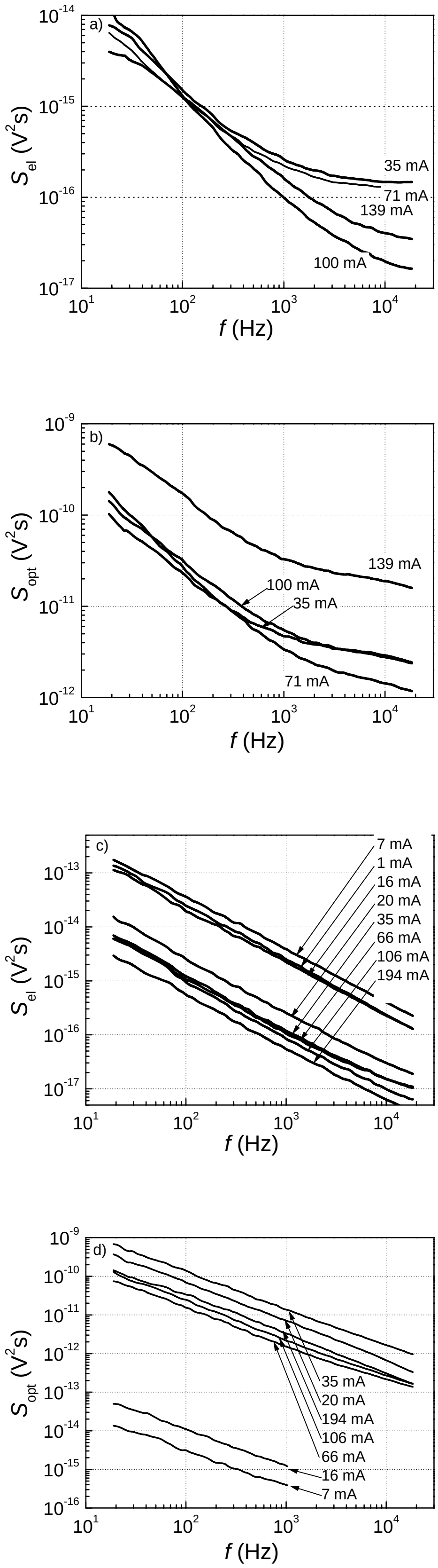

Fig. 2. Typical electrical (a, c) and optical (b, d) noise spectra for the FP laser at mode hopping peaks (a, b) and at stable operation (c, d) (sample A03)

intensity redistribution occurs [8]. This random mode intensity redistribution at defined forward currents and temperatures reflects in the noise characteristics as very intensive high-frequency and strongly correlated optical and electrical noises (solid line curves 1 in Fig. 1). Optical and electrical fluctuation spectra at the mode hopping noise peaks are Lorentzian type (graphs a and b in Fig. 2) while FP laser noise spectra at stable operation are 1/*f* type (graphs c and d in Fig. 2). Lorentzian type noise, characteristic for the mode hopping effect, is induced by interband recombination processes.

Investigation of facet coating influence on the mode hopping effect was carried out. The FP laser diodes with antireflection facet coating (less than 5 % reflection from the front facet) demonstrate much stable operation (dot line curves 2 in Fig. 1): there is no mode hopping noise peaks and operation and noise characteristics are similar to the DFB laser ones. Antireflection laser facet coating decreases resonator quality that leads to the significant reduction of the mode competition and less strict transition between different radiation spectra.

3.2. LD relithe ability and noise characteristic features

Looking for the laser diode noise features characteristic for the reliable lasers and LDs, whose lifetime is short, the groups of different quality samples have been investigated. Results of the not-aged lasers and samples after short burn-in (13 h at dc current 150 mA and temperature 100 ºC) were analysed.

Typical noise characteristics of the investigated DFB lasers at lasing operation are presented in Fig. 3. Electrical and optical noises for samples without ageing from the wafer A are larger than for ones after ageing (graphs a) and b) in Fig. 3): electrical noise is about a half order and optical noise is about an order of magnitude larger. Noise intensity decreasing after burn-in indicates that there are some defects in the lasers from the wafer A structure that during aging moves out of the active region, what leads to the better LD characteristics. That suggests that diodes from the wafer A need some burn-in to reach their optimal operation characteristics.

If compare lasers from different wafers: electrical noise level of DFB lasers from the better quality wafer B is similar to the not-aged lasers from the wafer A (graph a) in Fig. 2), while optical noise level is close to the burned-in sample from wafer A noise level (graph b) in Fig. 2). The result is determined by the defects that are not in the active region, where stimulated recombination occurs, and do not influence output light characteristics.

At lasing operation correlation factor between optical and electrical fluctuations of investigated DFB lasers is positive ((0 – 50) %, graph c) in Fig. 3), but decreases with the laser current increasing. There are two types of defects that originate optical and electrical noises: one of them causes noise components that are correlated positively, and others – negatively [9]. Defects that lead negatively correlated optical and electrical noise are located at the interface between active region and current blocking layers, they randomly redistribute laser current between active and passive regions and are related with lower laser diode quality and rapid degradation. The activation of these defects may be caused by larger current and/or higher

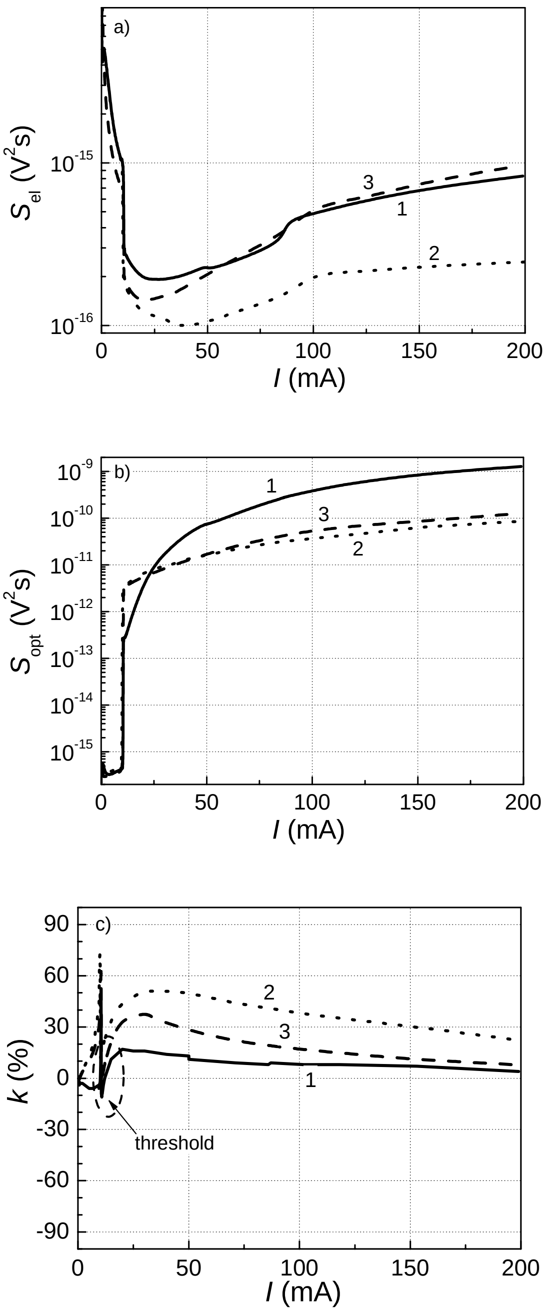

Fig. 3. Low-frequency noise characteristics for the investigated DFB lasers: a – electrical and b – optical fluctuation spectral density at 1.03 kHz, and c – correlation factor between optical and electrical noise signals in the frequency range 10 Hz – 20 kHz dependencies on laser current (curve 1 –not aged sample A12 (solid line), curve 2 – burned-in sample A13 (dot line), and curve 3 – burned-in sample B11 (dashed line))

Joule heating. It is observed that correlation factor at lasing operation for not aged samples from the wafer A is lower than for samples after ageing or lasers from the better quality wafer B (graph c) in Fig. 3), i. e. noise component with characteristic negative correlation is more efficient.

The FP laser noise characteristics investigation, if we do not pay any attention to the mode hopping effect (that effect was discussed in [8]), have shown the same features related with LD reliability as DFB laser noise

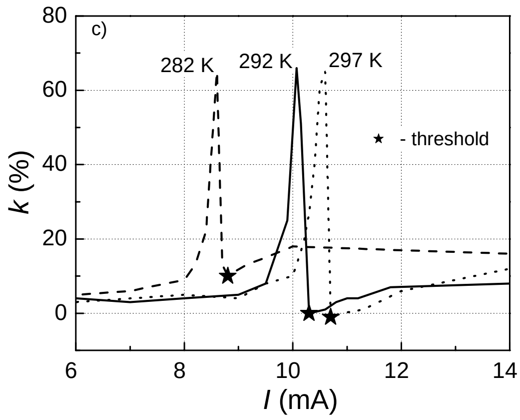

Fig. 4. Correlation factor between optical and electrical noise signals in the frequency range 10 Hz – 20 kHz dependencies on laser current in the threshold region at different temperatures (sample A12)

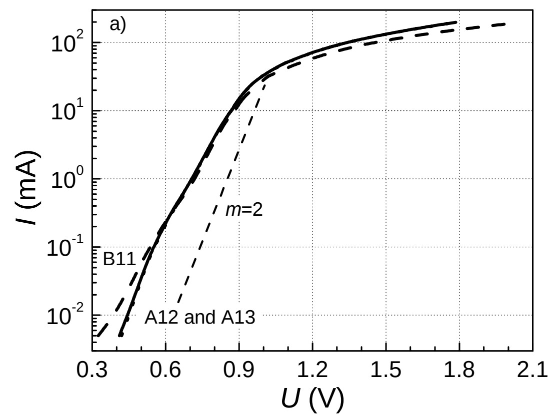

Fig. 5. Current-voltage characteristics for DFB lasers: sample A12 without ageing and burned-in lasers A13 and B11

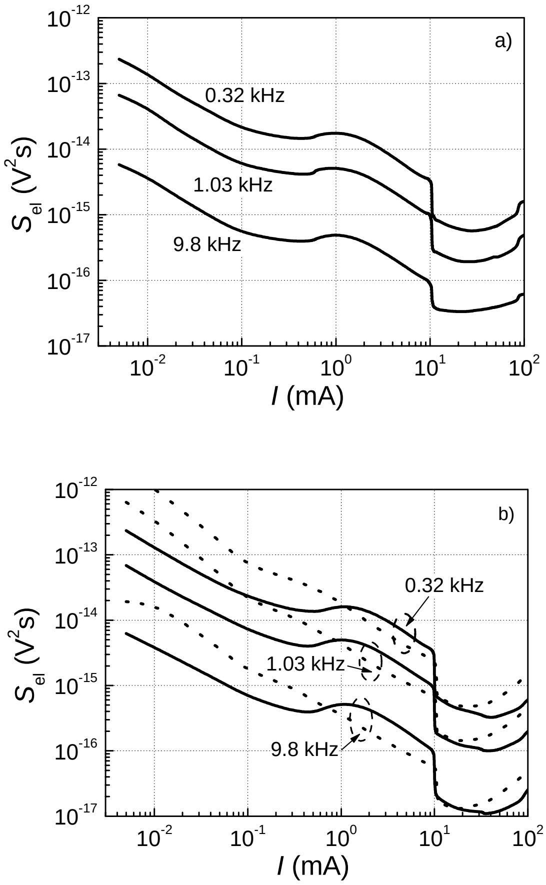

Fig. 6. Electrical fluctuation spectral density dependencies on laser current for investigated DFB lasers at three frequencies (0.32 kHz, 1.03 kHz and 9.8 kHz): a) sample A12 without ageing; b) burned-in samples A13 (solid line), and B11 (dot line)

characteristics.

During comprehensive study of laser diode reliability it was noticed that the most sensitive laser operation region to its quality and reliability problems is threshold and low bias regions: substantial information on LDs reliability can be obtained from the noise and current-voltage characteristics at threshold region and below one.

The correlation factor between optical and electrical fluctuations is especially sensitive to the processes that cause the poor LD reliability. Steep decrease of the correlation factor was observed at the threshold (graphs c) in Fig. 3 and Fig. 4): at threshold it is close to zero or negative. So, noise components with characteristic negative correlation are more intensive at threshold than at lasing operation region. Threshold LD operation characteristics are very sensitive to their quality, because operation at the threshold is very sensitive to the various fluctuations in the charge carrier number in active region: charge carrier number fluctuates around its threshold value. As it was discussed, defects, that induce negatively correlated optical and electrical noise component, randomly redistribute laser current between active and passive regions, herewith randomly change charge carrier number in active region.

Due to parasitic processes such as overflow of the injected charge carriers, Auger and other nonradiative recombination, intravalence band absorption the threshold current increases with temperature increasing (Fig. 4). It is observed that drop of correlation factor at the threshold increases with temperature increasing: from +10 % at 282 K to –1 % at 297 K. Thus, noise components with characteristic negative correlation become more intensive with temperature increasing, i.e. the defects related with poor laser diode reliability are more active at higher temperatures.

In Figs. 5 and 6, there are presented laser diode characteristics below the threshold: current-voltage and electrical noise characteristics. A non-ideality factor of current-voltage characteristic for investigated samples, both FP and DFB lasers, is in the range from 1.8 to 2.9. Non-ideality factor larger than 2 (latter value is one characteristic for good quality semiconductor diodes, where current flow is even through all *pn* junction surface, and the larger value of non-ideality factor the larger leakage current is implied) indicates non-uniform current flow and leakage current. Weak tendencies that non-ideality factor of lasers from the wafer B decreases with ageing (from 2.6 for sample B11 to 1.8 for LDs B12 and B13), and for diodes from the wafer A – increases (from 2.4 for laser A06 to 2.6 for samples A02 and A05), have been observed. Samples that demonstrate lower non-ideality factor distinguish by higher efficiency, i. e. better lasing characteristics. Electrical noise intensity below threshold decreases approximately proportional to the current increasing and has $1/f$ type spectrum (Fig. 6).

In the current region from 0.1 mA to 1 mA ((0.6 – 0.8) V) the investigated laser diodes have characteristic change of current-voltage characteristic slope (Fig. 5): at currents below this region non-ideality factor is smaller (about 2.3) than at current region above 1 mA to threshold (about 2.6).

In the current region where the change of non-ideality factor occurs a bump in the electrical noise spectral density dependency on laser current is observed (Fig. 6). Such bumps in the noise level dependency on current at small currents are characteristic for defective *pn* structures, when at certain bias a major part of current flows through the defect formed channels. Noise level increase at the bump in the sample from wafer A characteristics is notably larger than for lasers from wafer B (Fig. 6), what indicates more defective structure of diodes from the wafer A.

Electrical noise level of investigated lasers is quite similar at operation below threshold, and noise spectra are close to $1/f$ type over all investigated current region. It gets clear that large $1/f$ noise level at small currents does not give a definite answer on the quality of the device (if compare samples from the wafer A and B (graph b) in Fig. 6), it is seen that worse quality lasers from the wafer A have lower electrical noise level at low bias than better sample from the wafer B). This noise may be related to the leakage current through the peripheral areas of *pn* junction, and have no influence to the active layer and radiating characteristics. In study of laser diode quality and reliability an attention should be paid not only to the noise intensity, but to its character and dependency on laser current and temperature.

4. CONCLUSIONS

Comprehensive study of InGaAsP laser diode noise characteristics and their features relation with LD quality and reliability have been carried out.

It was found that Fabry-Perot (FP) laser facet coating with antireflection layer eliminates mode hopping effect (characteristic for the not coated FP laser operation) thus increasing FP laser operation stability: laser facet coating reduces resonator quality, what leads to the mode hopping effect disappearance.

It was shown that analyses of laser diode noise measurement results can be used to optimize the technological process for the laser fabrication: it was found that investigated lasers need additional burn-in that improves their operation and noise characteristics. Noise characteristic features that indicate low laser diode quality and short its lifetime are related with additional generation-recombination processes and leakage currents.

And conclusion that laser diode noise characteristic differences for reliable and unreliable samples are more informative at threshold region and below the threshold can be made. For the rejection of bad quality LDs it is enough to investigate noise and current-voltage characteristics in the vicinity of threshold region and at low bias.

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