Reliability and low-frequency noise measurements of InGaAsP MQW buried-heterostructure lasers

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Abstract — A laser diode reliability test based on the measurements of the low-frequency optical and electrical noise, and their correlation factor changes during short-time ageing is presented. The noise characteristics reveal obvious differences between the stable and unreliable lasers operated near the threshold region. An excessive Lorentzian type noise with negative correlation factor at the threshold could be one of the criteria for identifying unreliable lasers. The behavior of unreliable lasers during ageing could be explained by migration of point recombination centres at the interface of an active layer, and by the formation of defect clusters.

***Keywords* — laser diode, low-frequency noise, optical noise, electrical noise, correlation factor, reliability.**

Laser diodes (LDs) are extensively used as a signal source in fibre optical communication systems. High performance optical fibre systems need sources with a number of features: stable single-frequency output, gigabit/s modulation capability, stable operating lifetimes exceeding 10^8 hours at room temperature, and manufacturability. Buried heterostructure (BH) multiple-quantum-well (MQW) lasers possess performance characteristics that make them attractive for various applications. Optimization of the design parameters of the BH structure has led to a realization of very low threshold current, lower thermal resistance and stable transversal mode oscillation with nearly symmetric beam profile [1]. However, in the case of the BH laser, the complexity of the fabrication procedure (e.g. the requirement for additional growth steps as compared to a simple ridge-waveguide design) requires that rigorous attention be given to reliability concerns in order to meet product lifetime requirements. The degradation of BH structures is related to a decrease in the carrier lifetime or a decrease in non-radiative lifetime due to degradations of the edges of the active region [2, 3].

Product reliability is normally confirmed by accelerated ageing experiments, which take significant time and resources. As a result, there is a great demand for a simple, room-temperature device reliability screen to differentiate inherently reliable from unreliable production batches or devices. Low-frequency (LF) (usually $1/f$) noise is a typical excess noise that can be a very sensitive measure of the quality and reliability of optoelectronic devices [3–5]. Detection of LF noise can indicate the presence of imperfections. In addition, LF noise might be useful in providing insight into any changes observed during accelerated ageing experiments. In our preliminary work [6, 7] we have observed a correlation between the LD reliability and noise intensity. The LD reliability is also correlated to the degree of correlation between optical and electrical noise fluctuations. In this paper we report on the reliability test, that is based on the low-frequency optical and electrical noise, and how their correlation factor changes during short-time ageing at higher forward currents and at elevated temperatures.

The semiconductor lasers investigated in this paper are 1550 nm InGaAsP MQW BH gain-coupled, distributed-feedback (DFB) LDs with a thyristor-type p-n-blocking layer. Two experimental batches of LDs were chosen. The preliminary accelerated lifetime test (500 h, 150 mA, 100°C) showed that the threshold current degradation (increase by nearly a factor of 2 during the first 40 hours of operation) occurs during ageing for samples from one batch (these samples referred to as “unreliable devices” in this paper), while operation characteristics of samples from another batch were stable [6].

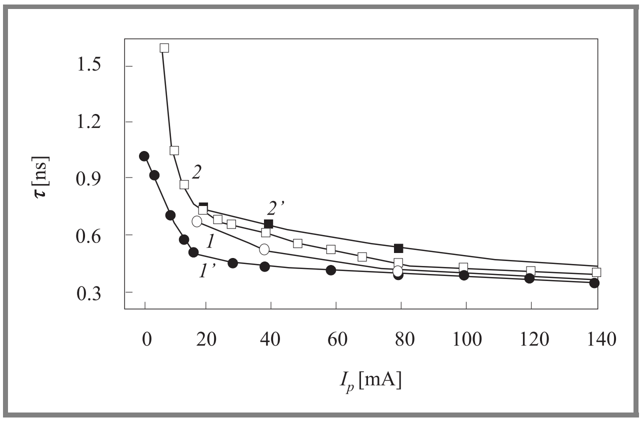

Fig. 1. The lasing delay time dependencies on pulse amplitude: *1* and *2* are respectively for stable and unreliable devices before ageing, *1'* and *2'* are respectively after 500 h ageing (measurement direct current is 5 mA, $T = 290$ K).

The voltage-current, optical output power and pulse characteristics were measured for all devices and then noise properties of a selected set of devices were analyzed. Threshold current for the stable devices was in the range of 6–8 mA, while for the unreliable ones ranged between 11–13 mA.

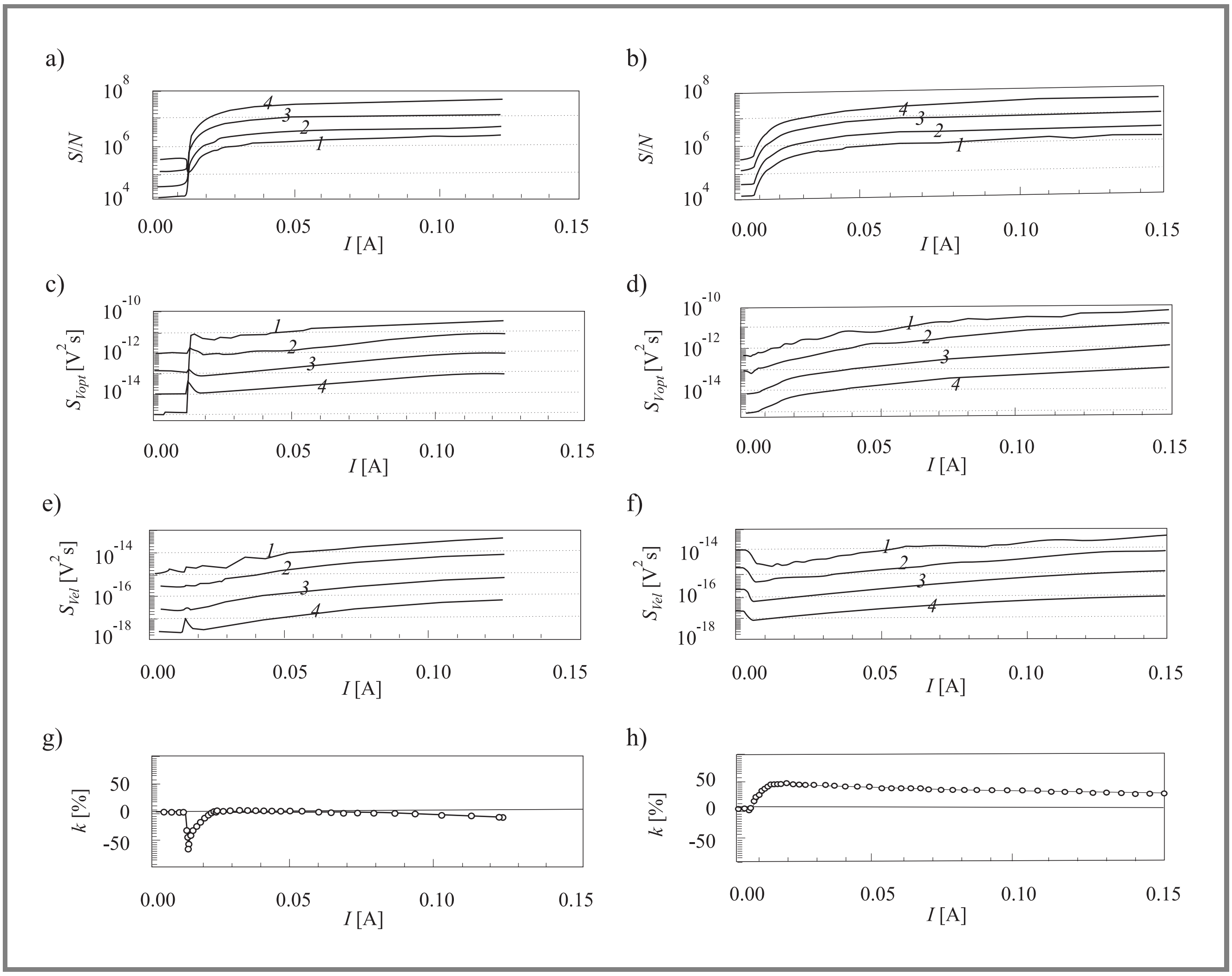

Fig. 2. (a, b) Signal-to-noise relation (S/N), (c, d) optical (S_{Vopt}) and (e), (f) electrical (S_{Vel}) fluctuation spectral density (*1* – 22 Hz, *2* – 108 Hz, *3* – 1.03 kHz, *4* – 10.7 kHz) and (g, h) correlation factor (k) (20 Hz–20 kHz) dependencies on laser current for unreliable (a, c, e, g) and stable (b, d, f, h) samples ($T = 290$ K; the devices were not aged).

Unreliable devices also have slower switching characteristics, too (Fig. 1): the lasing delay time for stable devices is in the range of 0.42–0.49 ns, while for unreliable ones is about 0.56–0.62 ns. In addition, a degradation of the switching characteristics during ageing for the unreliable devices was observed.

Noise characteristics (optical and electrical fluctuation spectral densities, optical signal-to-noise ratio and correlation factor between optical and electrical fluctuations) were measured at low frequencies (20 Hz–20 kHz). The noise measurement results for stable and unreliable LDs exhibited some differences in noise characteristics before ageing (Fig. 2). The noise intensity in the lasing operation region of samples from both batches was similar. However, the stable devices exhibit a strong positive correlation factor (30–60% for different samples) between the electrical and optical noises above threshold, while the unreliable devices exhibit a weak correlation. The reason for this difference is hypothesized to be due to defects in the semiconductor. The optical and electrical noise spectra are of $1/f$ type for all investigated LDs in the working current range. Various semiconductor growth and laser processing defects cause this noise. Positive correlation in the LDs operation shows that the devices contain defects that substantially modulate current flowing through the active region. However, the main differences were observed at the threshold region (transition from light emission diode to laser operation region): an increase of a high frequency component of the optical and electrical noise intensity (Fig. 2c and e, curve *4*) and negative correlation factor (30–70%) for different lasers (Fig. 2g) were observed for unreliable sample operation near the threshold. A high frequency component in stable samples has not been observed.

Further differences in the noise spectra of reliable and unreliable devices are observed close to threshold. Figures 3 and 4 present the optical and electrical noise spectra in the vicinity of the threshold current for the both types of devices before and after ageing. For unreliable samples (be-

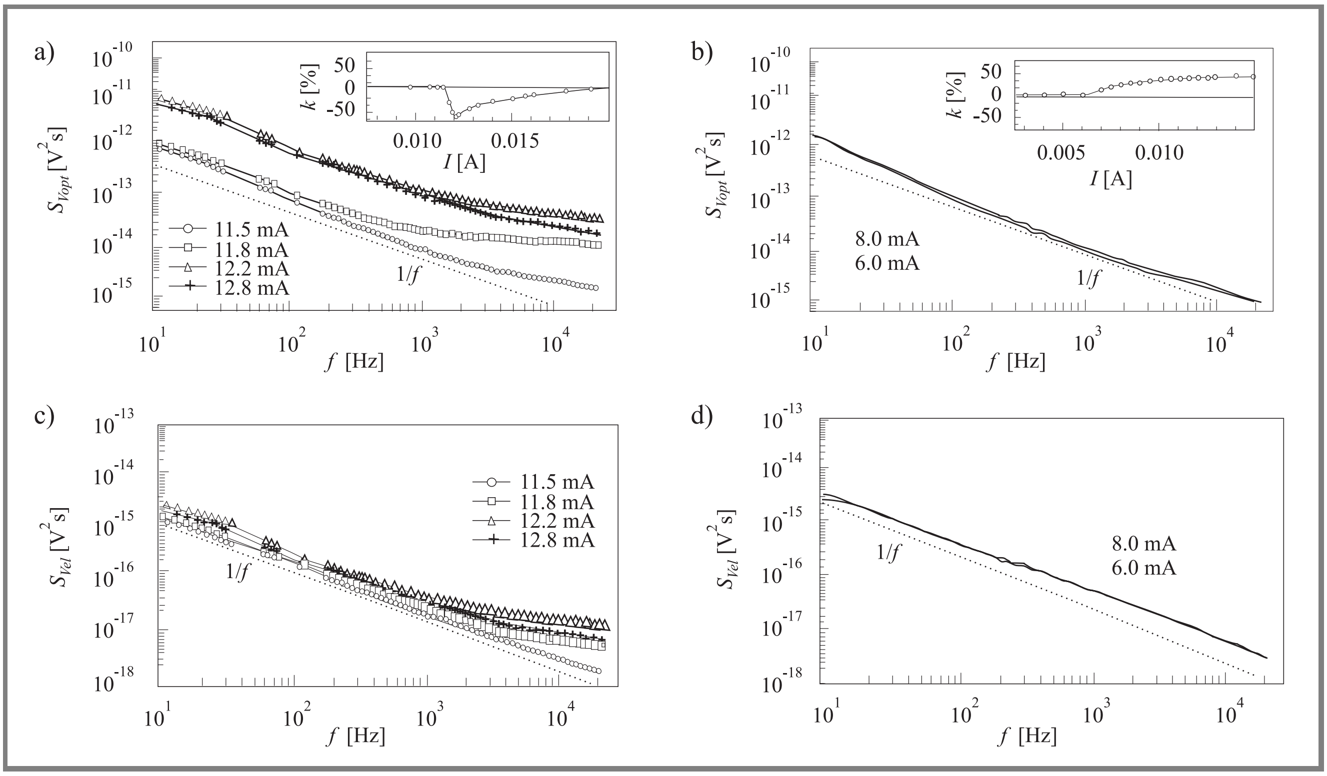

Fig. 3. Optical (a, b) and electrical (c, d) fluctuation spectra in the threshold region for unreliable (a, c) and stable (b, d) samples ($T = 290$ K; inclusion: correlation factor dependencies on laser current) (the devices were not aged).

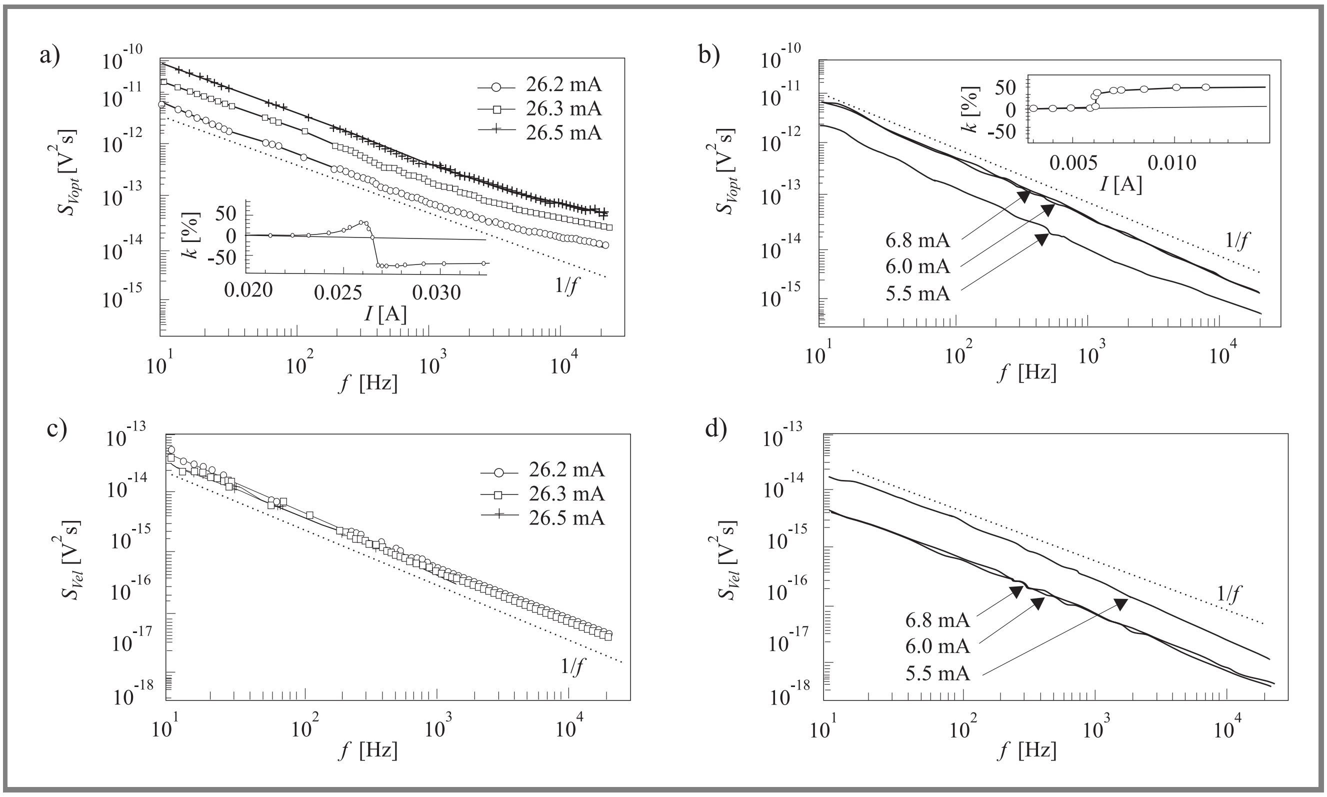

Fig. 4. Optical (a, b) and electrical (c, d) fluctuation spectra in the threshold region for unreliable (a, c) and stable (b, d) samples ($T = 290$ K; inclusion: correlation factor dependencies on laser current) (the devices were aged 500 h at 100°C and 150 mA).

fore ageing) excess high-frequency Lorentzian type (with the relaxation time of a few nanoseconds) electrical and optical noise component with negative correlation factor was observed (Fig. 3). A high frequency component for the stable samples has not been observed. The noise spectra for stable devices are approximately $1/f$ type. Furthermore, there is no correlation between optical and electrical fluctuations at the lasing threshold (Fig. 3). After ageing ($\sim$ 500 h) the unreliable devices exhibit a more intensive LF noise than before ageing (an optical noise spectral density increased by an order of magnitude) and the correlation factor at the threshold currents became positive (30–60%). There were no noticeable changes in the stable device noise intensity and other noise characteristics.

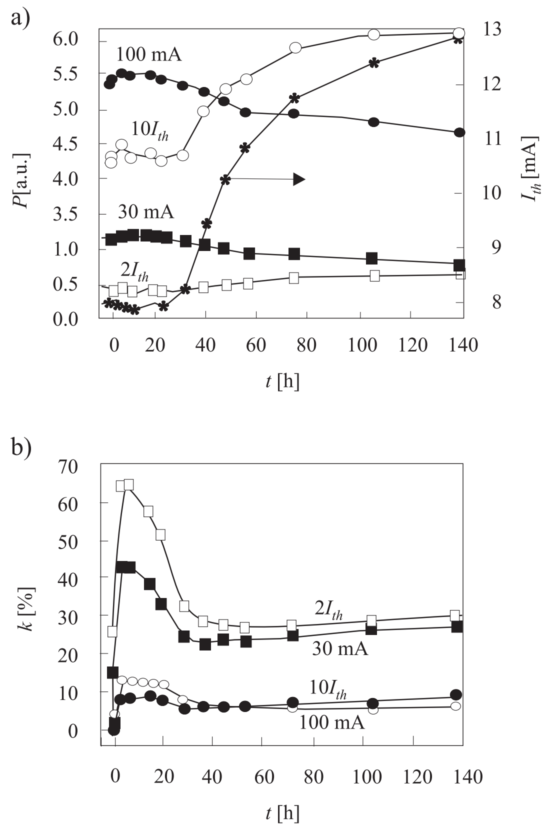

Fig. 5. Optical output power (P), threshold current (I_{th}) (a) and correlation factor (k) (b) dependencies on the ageing time for different laser currents of unreliable samples (ageing at 60°C and 150 mA, measurements at 290 K).

During ageing the high-frequency noise component of unreliable samples at the threshold decreased significantly (Fig. 4). This result can be explained by considering the noise sources of different origin. A recombination process that produces high-frequency fluctuations in both the laser resistance and the light output power commonly causes Lorentzian noise (i.e. the resistance and light output power fluctuate with opposite signs). On the other hand, cluster type defects are usually characterized by a wide distribution of relaxation times of charge carriers and, hence, produce a $1/f$ noise spectrum. It is hypothesized that during ageing at elevated temperature and high current densities the point (or other separated) defects responsible for Lorentzian noise migrate to form clusters (or macrodefects) at the active layer interfaces. Probably, the absence of such mobile defects in stable lasers can explain why the level and spectra of noises do not change during ageing for stable samples.

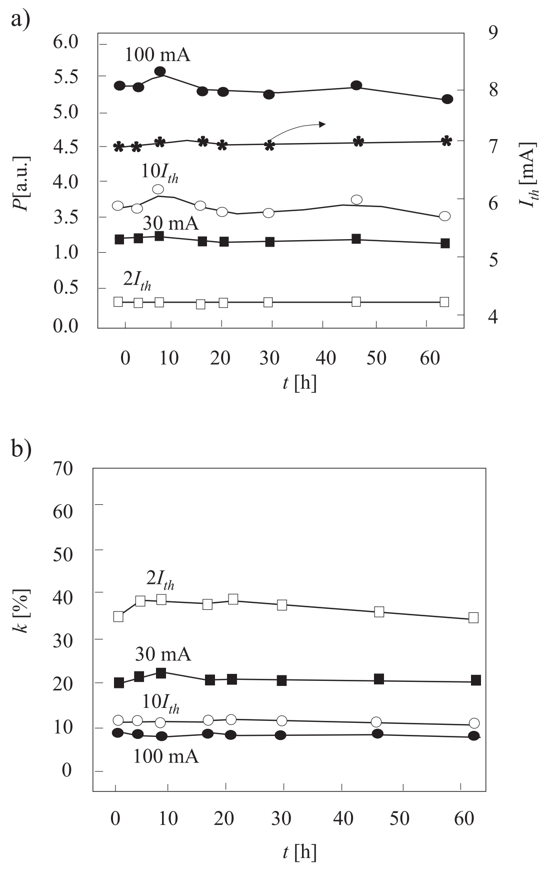

Fig. 6. Optical output power (P), threshold current (I_{th}) (a) and correlation factor (k) (b) dependencies on the ageing time for different laser currents of stable samples (ageing at 60°C and 150 mA, measurements at 290 K).

We have observed significant differences in noise characteristics at the vicinity of the threshold between LDs with good and poor reliability (Figs. 2 and 3). With that in mind, we conducted detailed short-time ageing experiments (ageing conditions: 60°C and 150 mA). Results of this experiment (Figs. 5 and 6) show that noise measurement method could be used as early LD reliability predictor. It could be seen that threshold current for unreliable devices does not increase in the initial phase of the ageing, while the noise characteristic changes are the largest in this phase: during the first 20 hours of ageing at comparatively low temperature optical noise spectral density increases by an order of magnitude and the correlation factor between optical and electrical fluctuations changes from 0 to 68% ($I \approx 2I_{th}$, Fig. 5). There is enough just to increase operation current up to 100 mA for the short time (few minutes) in order to change the correlation factor at threshold from -20% to $+18\%$. After ageing at rigid conditions (100°C) the unreliable samples above threshold have negative correlation factor (see inclusion in Fig. 4a), while after ageing at moderate conditions (60°C) a negative correlation was not observed (Fig. 5). This shows that defects migration and clusters formation way depends on the ageing conditions.

These results show that noise characteristics (especially the electrical and optical noise correlation factor) are a very sensitive measure of the device quality. We observed significant changes in the correlation factor, while changes of the total output power remain comparatively small. Conversely, as can be seen in Fig. 6, the noise characteristics of the stable laser diodes do not change during the short-time ageing at elevated temperature.

Conclusions. Noise characteristics reveal obvious differences in the reliable and unreliable lasers operated near threshold. Large high-frequency components in both optical and electrical noise and negative correlation factor between these parameters were observed in the unreliable lasers operation at threshold. Conversely, the reliable lasers exhibit no noise correlation change in the transition from spontaneous to stimulated emission.

After 500 hours of ageing at 100°C, and forward bias of 150 mA, the stable devices exhibited no measurable change in the noise spectra. However, both the optical and electrical noise of the degrading devices increased by an order of magnitude after ageing. It is believed that the changes in the unreliable devices operation characteristics (threshold current, output power, and noise characteristics) during the ageing are due to the migration of point recombination centres (responsible for the Lorentzian noise before the ageing) and formation of electrically active defect clusters (macrodefects) with a wide distribution of relaxation times.

Noise characteristics, and especially correlation factor between optical and electrical fluctuations, are very sensitive to the laser degradation and could be used as a powerful early predictor of reliability. This technique is especially useful in the case where the lifetest is performed at low temperature, in which a long endurance test is needed for the BH laser reliability evaluation.

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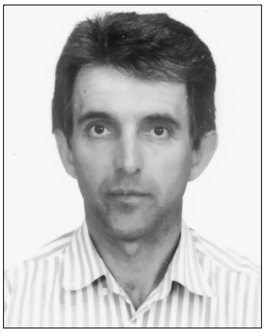

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